Under Pressure:
Generic and Individual Intra-oral Pressure Profiles in Liquid Swallows

Michael Guy Farland (BVSc BDS)

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Abstract

Aim: To determine if a universal pressure profile exists between healthy volunteers swallowing liquids of varying viscosity, and to investigate the effects of increased viscosity on these pressure patterns within and between individuals.

Methods: A custom made appliance with 7 miniature pressure transducers located along the mid-line and lateral palate was used to measure absolute pressures during 10ml water and honey-thick liquid swallows. Data were obtained from 10 healthy volunteers (5 males, 5 females; 22-42 years) with full permanent dentition. Following accommodation, subjects performed liquid swallows on command. Each subject performed swallows on 2 subsequent days yielding data from 12 swallows per individual for each liquid. Using the Scope® and Zoom® function of the LabChart® 7.0.2 software by ADInstruments, each individual’s pressure profiles were aligned at the initial major pressure peak of the mid-palatal channel to create an average swallowing profile for each liquid type. The average swallowing profiles from each individual were similarly overlaid to create generic average pressure profiles for each liquid.

Results: An underlying pattern common to all subjects was found within the highly variable individual pressure patterns. This was divided in to 4 stages: preparatory, primary propulsive, intermediate and terminal. To facilitate descriptive analysis, these stages were further sub-classified according to pressure patterns generated at the individual level. These were; tipper and dipper patterns in the preparatory stage, roller and slapper in the primary propulsive and monophasic or biphasic during the intermediate stage. Increased viscosity caused significant changes to these pressure patterns in certain individuals with little change in others. Stages most affected by increased viscosity were the preparatory and intermediate phases, whereas the primary propulsive stage was minimally affected. This highly individual response to increased viscosity was also observed with swallowing duration. Inter-individual variation of absolute pressures was too great to derive any significant change at the group level; however, negative pressure gradients were found to be associated with gathering of the bolus prior to the primary and secondary positive pressure clearing waves. Significant changes in absolute pressure values were found at the
individual level and these were highly variable with respect to region, symmetry and amplitude.

Conclusion: Despite highly variable individual absolute pressures, there was sufficient similarity in timing and polarity to describe a universal pressure profile. The closely related pressures generated anteriorly and laterally were consistent with a gathering of the bolus into a midline groove prior to a propulsive clearing wave along the midline. Despite this common swallowing pattern, widely disparate responses to increased viscosity occurred at the individual level. Average values were inappropriate for predicting an individual’s response to altered viscosity and as such, clinical interventions would be best aimed at the individual, rather than population level. The presence of an intermediate phase and secondary propulsive waves may indicate a less efficient clearance of the oral cavity and subsequently a greater risk of dysphagia. Further investigation on pressure profiles in geriatric, paediatric and dysphagic populations is required.

Key words: Intra-oral pressure, Pressure profiles, Transducers, Viscosity, Swallow, Tongue, Absolute pressure, Lateral pressure, Negative pressure, Bolus transit, Swallowing stages, Oral phase, Variability,
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Almost 3 years ago, I took my first hesitant steps on the journey that has ultimately resulted in this thesis. What I did not comprehend in those early days was the sheer size of that journey or the many hurdles that I would encounter along the way. It is with this in mind that I write these heartfelt thanks to the many wonderful people that have given up their valuable time to support and guide me to this destination.

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1 Introduction

A key question in oral biology research is the role of the tongue during mastication and swallowing. It is recognised that the sequential contact between the tongue and the palate plays a crucial role in the oropharyngeal phase of swallowing (Dodds, 1989; Hiiemae and Palmer, 2003). Despite numerous investigations into the nature and effects of tongue pressure generated during function, we still do not clearly understand how the tongue shapes the bolus and then transports it towards the oesophagus. Fundamental to bolus movement, as with any body at rest, is the application of a force of the appropriate magnitude, direction and timing. This not only initiates but also maintains bolus movement at an appropriate speed and direction.

Currently, there is limited research on the generation and coordination of absolute intra-oral pressures and regional pressure gradients. The focus of most research on intra-oral swallowing pressure to date has been on the generation of positive pressure by the tongue on the hard palate (Shaker et al., 1988; Poudreouk and Kahrilas, 1995; Nicosia et al., 2000; Ono et al., 2004; Youmans and Stierwalt, 2006; Steele et al., 2010). Further to this, most researchers have focused on the midline of the oral cavity. Consequently, we have only the most basic knowledge of the pressures developed within the oral cavity during the oral phase of the swallow. To better understand safe and efficient bolus transit through the oral phase of swallowing, we require further data on the appropriate timing, order and, most importantly, absolute magnitude of pressures generated. Ideally this would be throughout the entire oral cavity for the full duration of the swallow. The effects of altered bolus viscosity and volume on swallowing dynamics have been demonstrated in many studies. However these effects have yet to be thoroughly quantified (Dantas et al., 1990; Poudreouk and Kahrilas, 1995; Sugita et al., 2006; Taniguchi et al., 2008).

The key to optimal treatment of oral phase dysphagia, and the safe effective transition of the bolus through the oral cavity, is a thorough understanding of normal swallowing physiology. This not only allows accurate diagnosis, but also ensures that treatment strategies are appropriate and effective. However, there remains a lack of understanding
about the complexities of deglutition as well as the effects of bolus characteristics on efficient clearance to ensure airway patency (Nicosia and Robbins, 2001). Currently, in dysphagia management, liquids of increased viscosity are prescribed to help manage various swallowing disorders. An example of this is thickening liquids to a honey-like consistency to delay the flow into the pharynx of patients with delayed initiation of swallowing (Robbins et al., 2008; Steele and Cichero, 2008). Increasing our understanding of the effects of viscosity on intra-oral oropharyngeal pressures will add to the growing body of literature on dysphagia management and the dynamics of oropharyngeal swallowing.

The primary objective of this research project is to expand the knowledge of the patterns of absolute intra-oral contact pressure changes during swallowing. Specifically, it will focus on the similarities, as well as the differences, between individuals in the patterns (magnitude and timing) of changes in pressure during normal water swallowing and swallowing of a liquid bolus of increased viscosity. This study will link these individual pressure patterns in terms of the overall working of the swallowing apparatus with respect to bolus transit. The effects of increased bolus viscosity on the absolute intra-oral pressure generated during the transport of the bolus through the oral cavity will also be assessed, together with the potential effects of negative pressure on the bolus. This may refine the understanding of the oral phases of swallowing and have an impact on dysphagia management.

Most intra-oral pressure studies, including those by (Kieser et al., 2008; Kennedy et al., 2010) and (Kieser et al., 2011), who have developed this research methodology, have focused on the midline. This is largely due to the difficulty of placing multiple pressure sensors within the oral cavity and the significant complexity of analysing data from multiple pressure channels. With the benefit of significant advances in pressure transducer technology and post processing software, lateral palatal intra-oral pressures can now be investigated. Specifically, this research will investigate the timing and amplitude of the lateral pressures with respect to the midline and the subsequent effects of viscosity on these parameters. By increasing the understanding of the absolute pressure patterns generated across the full surface of the hard palate, there is potential to improve diagnosis and subsequent treatment strategies, for oral phase dysphagia.
The dilemma of low participant numbers is a significant issue in intra-oral pressure research. Contributory factors include the complex nature of data analysis and the expense of measurement devices suitable for the measurement of absolute pressure. For this reason, the existing database of command water swallows held in this research facility will continue to be developed as part of this study. This will allow future investigation of variables such as gender and to develop a substantive normative database from which to assess those with oropharyngeal swallowing disorders. Further development of a simple economical device to measure aspects of intra-oral swallowing pressure would become invaluable in the diagnosis and treatment of oropharyngeal dysphagia. Additionally, it could have significant impact on assessment and subsequent improvement of abnormal tongue function and posturing in orthodontics and speech therapy.
2 Literature Review

2.1 Tongue anatomy and function

The tongue is a muscular organ consisting of a highly complex interconnecting matrix of intrinsic muscles which, by convention, can only contract or relax but not actively lengthen. Within the limitations of muscular contraction, it must perform complex and rapid movements with extreme precision to allow speech and bolus manipulation. Further to this, the tongue possesses no internal rigid structures. It relies instead on the fact that it is an incompressible elastic structure contained within a fixed volume. As such, contractions of specific intrinsic muscles are able to cause elongation and motion whilst also providing the support for that motion. This is the fundamental of the tongue’s description as a variation of a muscular hydrostat. The result is that in the healthy adult, the complex patterns of extension, curling, flattening, and bending in multiple planes required of the tongue are achieved (Kier and Smith, 1985; Levine et al., 2005). In the tongue, recruitment of these intrinsic muscles is extremely complex as not only force for pressure generation must be controlled but so must maintenance of shape for bolus control.

Briefly, the 4 intrinsic muscles of the tongue consist of the superior longitudinal muscle and inferior longitudinal muscles that run along the length of the tongue beneath the superior and lateral inferior surface of the tongue. They act independently to curl the tongue up and down in the sagittal plane or in concert they shorten and thicken the tongue. The transversus muscle arises from the median fibrous septum and spreads laterally to the mucous membranes on each side to narrow the tongue or curl the lateral margins. Lastly the verticalis muscle runs between the superior and inferior longitudinal muscle and flattens the tongue (see figure 2.1)
Figure 2.1: Parasagittal (left) and coronal (right) illustration of a human tongue dissection. Intrinsic muscles: SL, superior longitudinal; IL, inferior longitudinal; T, transversus; V, verticalis. Extrinsic muscles: HG, hyoglossus; SG, styloglossus; GG, genioglossus. Taken from Miyawaki, (1974)

Coupled to this muscular hydrostat are the 4 extrinsic muscles that have either connective tissue or bony attachments (see figure 2.2). These are the palatoglossus, attached to the palatine aponeurosis; the genioglossus, attached to the genial tubercle; the hyoglossus, attached to the body and greater horn of the hyoid; and the styloglossus attached to the styloid process.
Figure 2.2: Lateral dissection of a human tongue with mandible removed. Extrinsic muscles shown; GG, genioglossus muscle; HG, hyoglossus muscle; SG, styloglossus muscle; PG, palatoglossus muscle. Taken from Kieser et al. (2011)

Unlike the situation with the self-supporting intrinsic muscles, which almost exclusively alter tongue shape, extrinsic muscle behaviour is largely limited to variations in levels of force and muscle recruitment. Subsequently these extrinsic muscles play a greater role in changes in tongue position within the oral cavity. One of the key factors relating to the tongue’s considerable mobility is that the only extrinsic muscle to attach to an immobile bony anchor is the styloglossus. Accordingly, Kieser et al. (2011) described the tongue as being “suspended from 2 muscular slings behind the ears”. It is also due to these anatomical constraints that tongue control and hence movement of the hyoid bone and the mandible necessarily affects pressure generation. These mobile bony anchors have a large range of motion due to their many other muscular insertions. These highly linked structures allow a seamless transition between the oral and pharyngeal phases of swallowing (Hiiemae and Palmer, 2003).
The nature of interaction between the intrinsic and extrinsic muscles has led to the theory that tongue control is achieved through independent yet overlapping functional segments. This theory stems from the consideration of muscular anisotropy with respect to insertion, orientation and size of muscle fibres. This is particularly evident in the sagittal plane with styloglossus and hyoglossus. This is also the case transversely, with extrinsic muscle insertion largely medial in genioglossus or laterally with hyoglossus or styloglossus (Stone et al., 2004). The anterior 2/3 of the tongue is a bilateral structure where extrinsic muscles do not cross the midline. Hence, the ability for symmetric elevation or asymmetric rotation is possible (Stone, 1990). As noted on parasagittal dissection by Kieser et al. (2011), in the most anterior zone of the tongue, the vast majority of muscle type found is intrinsic and there was found to be only minimal contribution from the genioglossus (see figure 2.3).

![Figure 2.3: Parasagittal thin sections of a human tongue and palate, hard palate; SP, soft palate; Ma, symphysis of mandible; Gg, genioglossus muscle; Lo, longitudinalis muscle.](image)

Taken from Kieser et al. (2011).

This theory of functional segmentation explains the regional variations in tongue behaviour. In particular, that seen during the early stages of the oral phase of the swallow, where complex bolus manipulation and containment is required. The later phases of the
swallow and posterior regions of the tongue have significantly more extrinsic muscle involvement as noted by the fact that tongue tip movement precedes the submental surface electromyographic (sEMG) burst. Therefore, due to the restrictions imposed by fixed and mobile skeletal attachments and the contraction-relaxation nature of their muscle recruitment, they would be expected to display a more uniform and stereotyped behaviour.

2.2 Swallowing physiology

A normal swallow occurs as a complex yet orderly physiological process that transports ingested material and saliva safely past the respiratory tract into the digestive tract. Swallowing occurs both under voluntary control via cortical input, and subconsciously, such as when clearing the oral build up of saliva between meals. Whilst awake this salivation occurs at approximately 0.5 ml/min and results in spontaneous swallowing at a rate of approximately 1/min or 1000 swallows per day. During sleep there is significantly reduced salivation and swallowing behaviour consequently almost ceases (Dent et al., 1980). Lear et al. (1965) studied 15 patients and found a mean number of 585 swallows per day.

Swallowing has been divided into phases for descriptive purposes. Magende (1817) originally described 3 phases as oral, pharyngeal and oesophageal (cited in Lear et al. 1965). Pouteroux and Kahrilas (1995) also described 3 phases of deglutition; the first being a loading phase, the second a pulsive phase and the last a clearance phase (Pouteroux and Kahrilas, 1995). Recent convention has utilised 4 phases (Dodds, 1989; Palmer et al., 2000; Logemann, 2007b). These are the preparatory oral phase, the oral propulsive phase, the pharyngeal phase and finally the oesophageal phase (see figure 2.4). The preparatory oral phase and oral propulsive phase are largely voluntary; however, the pharyngeal and oesophageal phases are considered to be involuntary (Dodds, 1989). Average durations of these phases in normal individuals are in the range of 1-2 s for the oral phases, less than 1 s for the pharyngeal and 8-10 s for the oesophageal phase (Logemann, 2007b).
2.2.1 The preparatory oral phase

The preparatory oral phase involves the mastication of food and mixing it with saliva into a bolus of suitable consistency, cohesiveness and volume. Being under voluntary control the duration of this phase varies considerably. Variables such as taste, temperature, texture and viscosity all contribute to this with sensory feedback from dorsal mucosa of the tongue (Logemann, 2007b). The tongue performs multiple rotary movements along its anteroposterior long axis thus directing its dorsum to the active chewing side (Abd-El-Malek, 1955). This, in conjunction with the buccal cheek muscles, allows repeated positioning of food between the teeth (Casas et al., 2003). During this phase the lips are sealed to prevent ingested material escaping and breathing is confined to the nasopharynx. Concurrently, the posterior tongue elevates against the soft palate to prevent premature entry of material into the pharynx (Dodds et al., 1990).

Prior to the onset of the oral propulsive phase of swallowing, the bolus is most often held on the dorsum of the tongue and the tongue tip presses against the palatal aspect of the maxillary incisors. This is the “tipper” type swallow described by Dodds et al. (1989), in their radiographic analysis of swallowing. In approximately 20% of subjects examined, the majority of the bolus was positioned beneath the anterior part of the tongue in the anterior sublingual sulcus. In these cases the tongue had to dip beneath the bolus to elevate it above the tongue. These so called “dipper” swallows were more prevalent in subjects 60 years or
older. Once the bolus was supra lingual, swallowing proceeded as for the tipper type subjects (Dodds et al., 1989).

2.2.2 The oral propulsive phase

The oral propulsive phase of swallowing delivers the bolus to the pharynx via a complex series of valve like openings and closures. The basic driving forces for the bolus are the tongue, palate and check muscles. With liquid swallows, the bolus is held in the midline groove and a spoon like depression in the anterior 1/3 to 2/3 of the tongue dorsum. This depression is thought to arise due to the tip, lateral borders and posterior tongue being pressed against the hard palate. With the lips sealed and the buccal muscles contracting, the tongue then elevates anteriorly sequentially, thus pressing the midline of the tongue onto the hard and soft palate in an anterior to posterior direction. This movement effectively obliterates the midline groove forcing the bolus into the pharynx and has been described as a posterior piston-like motion (Dodds et al., 1990).

At the same time as the tongue begins its posterior motion the following complex of events occur simultaneously; firstly, the base of the tongue moves down and forward, expanding the hypopharynx and simultaneously creating a funnel for the bolus to enter the pharynx. Next the palate moves upward opening the glossopharyngeal sphincter to encourage flow between the oral and pharyngeal cavities. The soft palate now contacts the posterior wall of the pharynx as the superior pharyngeal constrictors contract effectively sealing off the nasopharynx from the oropharynx. Lastly the posterior tongue, hyoid and larynx move upward and forward to expand the pharynx anteriorly as the pharyngeal levator muscle expand the pharynx transversely (Dodds et al., 1990).

To more accurately describe the coordinative organisation of the oral phase of swallowing, there have been various sub-stages proposed. Abd-El-Malik (1955) divided the oral phase of fluid deglutition into 3 stages. In stage 1, the closure stage, the anterior tongue pressed hard against the palate then creating a deep ”gutter-like form”. In stage 2, termed slide preparation, the tongue is rendered concave side to side and slopes obliquely downwards and backwards creating a smooth slope. Finally, in the pressure stage, the bolus is forced
by positive pressure out of the oral cavity into the pharynx. This early attempt to describe the swallow was significantly limited by imaging and access.

2.2.3 **Coordinative organisation of the oral phases**

This study will specifically record absolute pressure patterns generated during the oral phases of swallowing. As such, some discussion on other authors’ descriptions of the coordinative organisation of the oral phase of swallowing is warranted. Abd-El-Malik (1955) divided the oral phase of fluid deglutition into 3 sub-stages. In stage 1, the closure stage, the anterior tongue pressed hard against the palate then creating a deep "gutter-like form". In stage 2, termed slide preparation, the tongue is rendered concave side to side and slopes obliquely downwards and backwards creating a smooth slope. Finally, in the pressure stage, the bolus is forced by positive pressure out of the oral cavity into the pharynx.

With significant advances in imaging technology, Stone and Shawker (1986) observed the oral phase of swallowing with ultrasound and tongue surface pellet markers. They described 4 stages of tongue movement. The path of the movement was firstly, the forward stage, followed by the upward stage, steady stage, and finally the downward stage. Chi-Fishman and Stone, (1996) using electropalatography, (EPG) also identified 4 stages. These were the prep-propulsion, propulsion, full contact, and withdrawal stages. More recently, Peng et al (2004) divided the oral phase further into 5 sub phases as seen on M-mode ultrasound images. These were the shovel stage, early transport, late transport, early final and late final stages. Whilst informative, comparison between these various sub-stages is difficult due to variations in timing and methodology. Regardless of this difficulty, these sub-stages are necessary to allow accurate and repeatable qualitative and quantitative assessment of inter and intra-individual responses to multiple variables.

2.2.4 **The pharyngeal phase**

The pharyngeal phase of swallowing begins as the bolus reaches the faucial pillars. This and all subsequent phases are under involuntary neuromuscular control. The pharyngeal
phase consists of a rapid, complex series of overlapping events. As the bolus reaches the oropharynx the distal tongue makes a rapid posterior piston like motion which, coupled with sequential contraction of the pharyngeal constrictors caudally, propels the bolus through the pharynx. This pharyngeal peristalsis propagates at 9-25 cm/s (Dodds et al., 1990). As this occurs the airway is protected by 3 mechanisms. The elevation of the larynx, adduction of the true and false vocal folds and the epiglottis dropping over the top of the larynx directing the bolus towards the oesophagus (Logemann, 2007b). Bolus entry into the oesophagus is blocked by tonic contraction of the upper oesophageal sphincter (UES). UES relaxation is, therefore, crucial for this and lasts for approximately 0.5 s and allows bolus flow into the oesophagus (Kahrilas et al., 1988; Dodds, 1989). Opening of the UES results from a combination of traction from laryngeal elevation and the superior and anterior movement of the hyoid and is further augmented by the propulsive force of the descending bolus.

2.2.5 The oesophageal phase

Once the bolus and the pharyngeal peristaltic wave pass the cricopharyngeal muscle the upper oesophageal sphincter tightens and the oesophageal phase of the swallow continues. The proximal third of the oesophagus consists of striated muscle with purely involuntary innervation and its peristaltic motion behaves similarly to that of the more distal, circular smooth muscle. The bolus is preceded by a wave of muscular relaxation, which in combination with the peristaltic contraction behind effectively propels the bolus towards the stomach. The bolus is finally delivered to the stomach after it passes a relaxed gastro-oesophageal sphincter. This sphincter also plays a role in maintaining the seal between the acidic contents of the stomach and the upper digestive tract. The average oesophagus is 20 cm long and with a peristaltic propagation at 2-4 cm/s complete bolus passage takes between 6-10 s.

2.3 Rheology

Rheology is the study of the deformation and flow of material. It is crucial to have a sound understanding of the rheology of a material under study to enable comparison between
studies and to allow accurate prediction of its behaviour under various physiological settings in the management of disordered swallowing (dysphagia).

Viscosity is a measure of the resistance of a fluid to flow under an applied shear force. It is quantified by the ratio of shear stress to shear rate. Units of measurement of viscosity are poise (P) or pascal seconds (Pa s) and 1 centipoise (cP) is equivalent to 1 millipascal second (mPa s). A unit of 1 cP has been ascribed to water at 20°C (Steele et al., 2003).

Fluids can be described as Newtonian and non-Newtonian. Newtonian fluids, such as water have a linear relationship of flow to shear stress. This is not the case with non-Newtonian fluids. Here flow is not proportional to the shear stress applied. Most dietary liquids are non-Newtonian and, consequently, their viscosity varies depending on the shear rate being applied to them. There has been a very wide range of lingual shear rate estimates in previous research. Ranges from 5 s⁻¹ to 1000 s⁻¹ have been used and to date there has been little consensus (Steele and Van Lieshout, 2004). Shear rates affect non-Newtonian fluids by decreasing their viscosity as shear rates increase. This effect is termed shear-thinning (Garcia et al., 2005).

In addition to viscosity, density and yield stress have an effect on the flow and behaviour of a bolus during swallowing. These also have the potential to alter the behaviour of a bolus sufficiently to be clinically relevant in the management of dysphagic patients. To date there has been very little research into the effects of fluid behaviour other than viscosity (Nicosia and Robbins, 2007).

Yield stress is the behaviour of certain non-Newtonian fluids such as pastes or thick suspensions that do not flow until a critical stress is reached. A common example of this phenomenon is tomato ketchup that needs to be banged to initiate flow from the bottle (Nicosia and Robbins, 2007). Most dietary liquids and the cornstarch or gum-based liquid thickeners used in dysphagia management are non-Newtonian fluids that display yield stress properties (Steele et al., 2003).

Density is the mass per unit volume (g/cc) of a fluid and closely relates to its weight. Dantas et al., (1989) studied high- and low-density barium preparations. Studying 5 and 10
ml swallows revealed that the low-density barium (1.4 g/cm3) preparation had a slower oral and pharyngeal bolus transit time than the high-density barium (2.5 g/cm3). Density also has an effect on the behaviour of a fluid of the same viscosity. The line spread test is used to broadly categorise the consistency of thickened foods in dysphagia management. Nicosia and Robbins (2007) demonstrated that dense fluid such as barium spreads further than a less dense fluid of the same viscosity.

Nicosia and Robbins (2001) designed a simplified model of a squeezing flow between 2 plates to approximate the tongue as a rigid body and the hard palate. They found that with increased viscosity and density of a liquid the time to clear the bolus increased and with increased pressure the clearance time decreased. This model showed that for a low-viscosity liquid of less than 100cP, the bolus density had a greater effect on bolus clearance time. A transition period occurred during the 100-1000 cP range then above this, viscous properties overcome the inertial effects required to accelerate a static bolus. These findings were of significance especially when comparing low-viscosity, high-density liquids such as barium sulphate (frequently used in diagnostic swallowing studies) to low-viscosity, low-density liquids normally found in the diet. Though the experimental changes in clearance time noted were small, the oropharyngeal phase of swallowing was correspondingly fast with completion in the vicinity of 100msec (Kahrilas et al., 1993).

In 1997 Smith and his co-workers investigated oral perception of a range of 7 non-Newtonian fluid viscosities. These ranged between 3 and 2240 cP. The subjects found that they were able to accurately perceive thin, middle and thick viscosities. However accuracy declined as the viscosity increased above 200 cP requiring substantial changes to accurately discriminate (Smith et al., 1997). In a later study, Steele et al. (2003) compared the measured viscosity of a liquid to that perceived subjectively by clinicians. Clinicians were found to be able to differentiate relative viscosity and density differences between nectar- and honey-thick items after stirring, oral manipulation and by weight (Steele et al., 2003).

Garcia et al.(2008) investigated the behaviour of thickeners under the influence of various serving temperatures. They found that only fully gelatinised starch based thickeners followed the Arrhenius relationship where increases in temperature resulted in a
proportional decrease in viscosity. However, starch suspensions that had not fully gelatinised resulted in further swelling of granules under heating, causing an increase in viscosity as they reached their gelatinization temperature. As a result of this behaviour starch based thickeners become more viscous as they move either direction from 25°C.

Gum based thickeners, on the other hand, decrease in thickness with increasing temperature. The exception of this is Xanthan gum which is relatively stable from 0-100°C (Garcia et al., 2008).

2.4 Factors affecting swallowing behaviour and tongue dynamics

2.4.1 Saliva versus liquid swallowing

Hamlet, (1989) investigated the dynamics of dry (saliva only) and liquid swallows. Less lingual movement was noted in the saliva swallows. They were also initiated higher on the palate compared to those of normal liquid swallows where the tongue position was below the incisal plane. The cross sectional contour of the tongue was humped or flat in saliva swallows, whereas it was grooved for liquid. This suggested that saliva swallows were dissimilar to even small volumes of water due to the subject’s awareness of a bolus in the oral cavity (Hamlet, 1989). However, due to the behaviour of saliva gathering from the oral cavity under negative pressure prior to swallow, final clearance of the bolus may be significantly affected in the case of loss of anterior oral seal.

2.4.2 Volume

Dantas et al. (1990) found that increased volume resulted in an earlier onset of anterior tongue base movement, superior palatal movement and UES opening. These were all adaptations necessary for receiving the bolus (Dantas et al., 1990). Miller and Watkin in (1996) found no differences in linguo-palatal forces with variations in volume. However they did hypothesise that with increased volume more intrinsic muscular force would be required to maintain an adequate lateral and anterior seal (Miller and Watkin, 1996).
2.4.3 Taste

Studies on the effect of tastants on swallowing parameters have consistently found that increasing intensity of bolus tastants affected swallowing parameters (Logemann et al., 1995; Chee et al., 2005; Leow et al., 2007; Pelletier and Dhanaraj, 2006). It was suggested that the increased stimulus provided an effective pre-swallow sensory input, which lowered the pharyngeal swallow threshold (Palmer et al., 2005). Leow et al. (2007) found that sweet tastants had a shorter oral preparation time than bitter tastants and longer swallowing duration than bitter salt and sour tastants. This was similar to the recent study by Palmer (2005) in which sour boluses were found to increase swallowing effort compared to other tastes. Pelletier and Dhanaraj (2006) investigated the effect of tastants on lingual swallowing pressure in healthy adults. They noted that moderate sucrose; high salt and high citric acid resulted in significantly elevated swallowing pressures compared to water swallows.

2.4.4 Age

Vaiman (2004) reported a clear tendency toward a volume decrease in separate and continuous water swallows with increasing age. The 18-40 year average was 16.5ml and in the 70+ age group it was 12ml (a 31% decrease).

2.4.5 Viscosity

There is a growing body of literature suggesting that bolus consistency has significant effects on the physiology of the oropharyngeal swallow. Early investigations on anterior lingual force used strain gauges to record pressures between the tongue and the palate. They found changes in viscosity altered the pressure achieved by the piston-like forces of the tongue against the palate (Proffit et al., 1964; Proffit, 1972; Kydd and Toda, 1962).

Later, Pouderoux and Kahrilas (1995) used pressure sensing bulbs and strain gauge manometry to assess alterations in pulsive force and clearance pressures in oropharyngeal swallowing. Their findings showed a profound increase in pulsive and clearance pressures on effortful swallows and with increased viscosity. They also noted that alterations to volition and viscosity resulted in higher pressures in the mid and anterior tongue, with minimal changes in the posterior tongue and tongue base.
Dantas et al. (1990) found that increased bolus viscosity resulted in delays to oral and pharyngeal bolus transit and clearance from the oropharynx. It also resulted in increased duration of the pharyngeal peristaltic waves as well as increased and prolonged UES opening. They also found that intra-bolus pressure was increased with increased viscosity. A study by Reimers-Neils et al. (1994) focused on the effects of viscosity on electromyography (EMG) activity in normal swallowing. They found an increase in duration with increasing consistency and increased EMG activity between the thin and the thick consistency. They proposed that this indicated an increased muscular effort (Reimers-Neils et al., 1994). Miller and Watkin (1996) used force transducers to measure linguo-palatal forces and found that increased viscosity resulted in a significant increase in lingual force on the hard palate. They hypothesised that increasing viscosity required increased force to initiate bolus flow. They also suggested that bolus volume affected the anterior and lateral margins of the tongue to accommodate the bolus and maintain a palatal seal (Miller and Watkin, 1996).

Steele and Van Lieshout (2004) utilised electromagnetic mid-sagittal articulography of the tongue dorsum. They found only minor effects on lingual movements in viscosities ranging between nectar- and honey-thick liquids. These effects were limited to increasing overall duration of oropharyngeal transit as measured by swallowing frequency and movement variability of the posterior dorsum of the tongue.

Sugita et al. (2006) measured anterior and posterior tongue pressure using 8 mm diameter pressure sensors at the anterior and posterior hard palate. They noted that with increased consistency, a corresponding increase in peak amplitude in posterior tongue pressure occurred. This finding was not seen in the anterior palate. This was in contrast to the findings of Pouderoux and Kahrilas (1995). They also noted a wide inter-individual response suggesting significant variety in individual swallowing behaviour. At the anterior tongue they noted an increase in duration of tongue pressure with increasing consistency. Taniguchi et al. (2008) studied viscosity and hardness of the bolus and its effect on swallowing dynamics. Using videofluorography in conjunction with anterior and posterior palatal pressure sensors, they found that increasing consistency of a bolus increased total swallowing time and oral ejection time. The increase in viscosity was found to have a greater effect on pharyngeal clearance and transit time. They also demonstrated that the
posterior tongue alone had an increase in pressure with no significant difference on the anterior tongue palatal pressure, which is similar to the findings of Sugita et al. (2006).

2.5 Unequal tongue pressures

In the analysis of lateral tongue behaviour, several studies employing strain gauges have demonstrated asymmetrical lateral forces between the tongue and the hard palate (Kydd and Toda, 1962; Proffit et al., 1964; Proffit, 1972). Miller and Watkin (1996), who attached lingual force transducers to the anterior right and left lateral tongue, also found consistent individual asymmetry on the lateral margins of the tongue across their small study population. They also found that some individuals displayed a consistent preference to right or left sided swallows. Interestingly Ono et al. (2004) using their positive pressure sensors found no laterality across their group averaged values at the anterior and posterior lateral sensors. They did not, however, report on individual differences.

2.6 Dysphagia

Smith Hammond and Goldstein, (2006) defined dysphagia as “abnormal swallowing due to impaired coordination, obstruction or weakness affecting swallowing biomechanics.” This condition is especially common in the elderly and has a significant morbidity and mortality associated when poorly managed or undiagnosed. The most immediate risk of dysphagia is entry of the bolus into the airway instead of the oesophagus.

The most serious results of airway compromise are obstruction or aspiration pneumonia. The effects of obstruction are immediate and potentially catastrophic. Aspiration effects are highly variable and severity of the outcome depends on the quantity, depth of penetration and physical properties of the aspirate as well as local airway and systemic health (Palmer et al., 2000). The terms penetration and aspiration have been used to describe varying degrees of airway compromise. Penetration results if the bolus enters the larynx to the level of the vocal folds whereas aspiration is used should the bolus traverse this barrier and enter the trachea (Smith Hammond and Goldstein, 2006). It should be noted that penetration and aspiration are the results of dysphagia and are not disorders in
themselves. Penetrance and aspiration carry a 4-fold and 10-fold risk of pneumonia respectively (Pikus et al., 2003).

Aspiration pneumonia is the most common form of hospital acquired pneumonia and occurs in 4-8 per 1000 hospitalised patients in the United States. This life-threatening condition has reported mortality rates ranging from 20-62% (Pikus et al., 2003). It is obvious that appropriate diagnosis and management of dysphagia is crucial, not only in the care of hospitalised or elderly patients but also in any population at risk of dysphagia. Of particular concern are patients who display silent aspiration without any overt signs or symptoms of respiratory tract compromise. In these cases the patient has an absent cough reflex following aspiration either before, during, or after swallowing and it has been reported in as many as 40% of aspiration cases. As a result of the difficulty in diagnosis, patients with silent aspiration are 13 times more likely to develop pneumonia (Pikus et al., 2003). Patients at particular risk of silent aspiration include those with neurologic impairment. In particular Alzheimer’s disease, Parkinson’s disease, seizure disorders, cerebrovascular disease, trauma and brain or cervical surgery patients. Patients with vocal fold paralysis, bronchitis, laryngopharyngeal reflux and those recovering from coronary artery bypass and head and neck radiation are also at high risk (Smith Hammond and Goldstein, 2006).

It is not only aspiration of the bolus and resultant respiratory tract complications that is of concern to dysphagic and institutionalised patients. Clearly inadequate food intake can lead to malnutrition. Often thickened liquids are used in the management of dysphagia. However if the patient perceives it as too thick it is often rejected which leads to insufficient hydration. This dehydrated state can result in increased predisposition to urinary tract infections, pneumonia, decubitus ulcers, and confusion, which can be misidentified as dementia. Such patients are also at risk of significant electrolyte imbalances with dangerously high serum levels of sodium and potassium (Dewar and Joyce, 2006). As well as these physiological consequences there are often significant secondary effects including social isolation and depression (Smith Hammond and Goldstein, 2006).
2.6.1 Aetiology and classification of dysphagia

Dysphagia results from the derangement of the normal swallowing sequence. Rather than a discrete disease entity, it is a symptom of a wide range of systemic and localised disorders that can affect any part of the entire swallowing process (see table 2.1). Deficiencies in neurological or muscular function, structural lesions, connective tissue diseases, iatrogenic causes and psychiatric disorders can all lead to dysphagia. Almost any medical diagnosis that causes generalised weakness will result in some level of oropharyngeal dysphagia.

Table 2.1: Causes of oral and pharyngeal dysphagia after Palmer et al., (2000).

<table>
<thead>
<tr>
<th>Neurologic disorders</th>
<th>Structural lesions</th>
<th>Others:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral infarction</td>
<td>Thyromegally</td>
<td>Psychiatric disorder:</td>
</tr>
<tr>
<td>Brain stem infarction</td>
<td></td>
<td>Psychogenic dysphagia</td>
</tr>
<tr>
<td>Intracranial bleeding</td>
<td>Cervical hyperostosis</td>
<td></td>
</tr>
<tr>
<td>Parkinson’s disease</td>
<td>Cerebral hyperostosis</td>
<td></td>
</tr>
<tr>
<td>Multiple sclerosis</td>
<td>Congenital web</td>
<td>Connective tissue diseases:</td>
</tr>
<tr>
<td>Atrophic lateral sclerosis</td>
<td>Zenker’s diverticulum</td>
<td>Poliomyositis</td>
</tr>
<tr>
<td>Poliomyositis</td>
<td>Caustic ingestion</td>
<td></td>
</tr>
<tr>
<td>Myaesthenia gravis</td>
<td>Neoplasia</td>
<td>Iatrogenic causes:</td>
</tr>
<tr>
<td>Dementias</td>
<td></td>
<td>Surgical resection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radiation fibrosis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medications</td>
</tr>
</tbody>
</table>

Impairment of the oral phases of swallowing usually stem from disruption to normal tongue function. However, lip, cheek muscle or dental pathology may also be involved to varying degrees (Palmer et al., 2000). Essentially, there is an impairment of the containment and delivery of the food bolus resulting in various sequelae. These include, premature spillage out of the mouth, poor clearance of the buccal vestibules or oral cavity, or delivery of the bolus into the unprepared pharynx, thus risking aspiration.

Odynophagia is defined as painful swallowing. Dysphagia can present with or without pain but odynophagia often causes a secondary dysphagia due to alterations in the voluntary oral phase of swallowing. Causes include dental or oral infections, salivary gland pathology and following oro-facial surgery complications. Reduced buccal or labial
tension, poor dentition, masticatory muscle disorders and lip incompetence should be noted in any diagnostic workup as potential causes of dysphagia (Vaiman and Nahlieli, 2009).

Pharyngeal phase impairment results in failure of delivery of the bolus to the oesophagus and causes retention of bolus material in the pharynx after the swallow is completed. In normal patients small amounts of material may be left in the valleculae or piriform sinus after swallowing. In pharyngeal dysphagia however, this amount becomes excessive and puts the patient at significant risk of aspiration. This is especially the case if the physical laryngeal protective mechanisms or cough reflex are impaired. Weakness of the soft palate and pharynx can lead to nasal regurgitation due to failure of the velopharyngeal seal. Insufficient tongue base movement resulting in poor contact with the pharyngeal wall can also lead to excessive pharyngeal residue as can an ineffective pharyngeal peristaltic contraction (Logemann, 2007b; Palmer et al., 2000).

In addition to weakness of the pharyngeal musculature, delay or absence of pharyngeal swallowing triggers can lead to an unprepared airway and bolus aspiration. It is understood that this triggering occurs in the medulla of the brainstem; however, the sensory or motor inputs required to stimulate a response are as yet unknown (Logemann, 2007b). In the final stage of swallowing, dysphagia manifests as retention of food in the oesophagus. Impaired peristalsis, mechanical obstruction, fibrosis or malfunction of the lower oesophageal sphincter can all be causative.

2.6.2 Diagnosis

The diagnosis of dysphagia is complicated. It is usually based on recognition of sometimes-subtle clinical signs and careful history taking (see table 2.2). Many patients with dysphagia are unaware of their condition and this is especially true of patients with silent aspiration. Once the condition is identified, the location of the region involved and the underlying aetiology must be sought so as to maximise an effective management plan.
Table 2.2: Clinical signs of dysphagia after Palmer et al., (2000).

<table>
<thead>
<tr>
<th>Oral and pharyngeal dysphagia</th>
<th>Oesophageal dysphagia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing or choking with swallow</td>
<td>Sensation of food sticking in throat</td>
</tr>
<tr>
<td>Difficulty initiating swallow</td>
<td>Oral or pharyngeal regurgitation</td>
</tr>
<tr>
<td>Food sticking in throat</td>
<td>Drooling</td>
</tr>
<tr>
<td>Drooling</td>
<td>Unexplained weight loss</td>
</tr>
<tr>
<td>Unexplained weight loss</td>
<td>Change in dietary habits</td>
</tr>
<tr>
<td>Change in dietary habits</td>
<td>Recurrent pneumonia</td>
</tr>
<tr>
<td>Recurrent pneumonia</td>
<td></td>
</tr>
<tr>
<td>Change in voice or speech</td>
<td></td>
</tr>
<tr>
<td>Nasal regurgitation</td>
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</tr>
</tbody>
</table>

Once a suspicion of oropharyngeal dysphagia exists, a thorough medical examination with an emphasis on disorders described previously is essential. Following this, referral to a speech-language pathologist allows a thorough evaluation of the nature and severity of the dysphagia. Assessment involves detailed history taking and oral examination with an emphasis on the anatomical and physiological assessment. This is followed by a functional assessment of lip, tongue and palate strength and mobility (Logemann, 2007b).

Subjective measures of tongue strength including lingual lateralisation and protrusion forces have a high correlation with oral phase dysphagia in the hands of experienced examiners. Objective measures of tongue strength have also been utilised in screening of dysphagia patients. The Iowa Oral Performance Instrument (IOPI) is one such device that has a large body of normative data performance reference ranges when assessing maximal and average tongue strength. Clark et al. (2003) found a poor correlation with oral clearance and objective measures of tongue strength. However, they and others have also found that objective measures of tongue strength are good predictors of oral phase dysphagia (Clark et al., 2003; Stierwalt and Youmans, 2007).

If the dysphagia is thought to be pharyngeal in origin then dynamic imaging methods such as a modified barium swallow or videoscopic swallow evaluation (VSE) are necessary.
These radiographic studies allow relatively precise analysis of the anatomy and pathophysiology of the patient’s swallow under various volumes and food consistencies (Logemann, 1997). Importantly, it also allows assessment of rehabilitation strategies to minimise the chances of aspiration and inadequate bolus clearance from the pharynx. Due to the vast amount of diagnostic and intervention outcome information gathered by this investigation, it is considered the gold standard for swallowing evaluation and dysphagia management (Palmer et al., 2000). Certain contraindications exist for its use and these include absent command swallow, lethargy, inability to manage oropharyngeal secretions and respiratory rate greater than 35 breaths per minute (Smith Hammond and Goldstein, 2006).

There are other diagnostic studies available for dysphagia assessment. These include oesophagoscopy for suspected oesophageal dysphagia and the fibreoptic endoscopic examination of swallowing (FEES) for pharyngeal dysphagia. The FEES utilises a laryngoscope passed via the nasal cavity to evaluate pharyngeal clearance. It is very good at identifying aspiration and pharyngeal retention; however, the lens is obscured during much of the swallow due to contraction of the pharynx and the bolus. As a result it is unable to analyse functional aspects of the pharyngeal swallow such as level of laryngeal elevation, tongue base movement or upper oesophageal sphincter function. Ultrasound can also be used to look at oral stage dysphagia and manometry of the pharynx in conjunction with radiography has been documented.

2.6.3 Management

Due to the complex nature of oropharyngeal swallowing and potentially fatal consequences of dysphagia, a team-based approach to management is considered to be essential (Logemann, 2007b; Smith Hammond and Goldstein, 2006; Association, 1999). The individually designed treatment protocol required by dysphagic patients may require incorporation of a physician, neurologist, otolaryngologist, gastroenterologist, radiologist, nurse, occupational, physical and speech language therapists and a dietician (Smith Hammond and Goldstein, 2006; Logemann, 2007a).
Depending on the diagnosis, multiple treatment modalities may be employed. These include dietary modification, swallow therapy and in rare cases surgery to relieve obstructions or to decrease resistance of the upper oesophageal sphincter. In all cases follow up of management strategies by modified barium swallow or VSE is essential to ensure that the interventions strategies are indeed effective (Logemann, 1997). As volume and viscosity affect swallowing in differing ways (Dantas et al., 1990), dietary modification involves individually selecting the ideal consistency and volume of bolus for each new patient. Dysphagic patients vary in their ability to swallow thick and thin liquids. For example, patients with delayed pharyngeal swallow triggering readily aspirate water swallows. Increasing the bolus viscosity delays the transit time during the oral phase and reduces aspiration. In others too high a viscosity can increase the level of dysphagia due to the increased forces required to move the bolus (Miller and Watkin, 1996). A pureed diet is recommended for those with dysphagia of the oral preparatory phase, who tend to pocket the food in their buccal vestibule or have pharyngeal retention of chewed solid foods (Palmer et al., 2000). Sensory modification by altering bolus temperature, taste or texture have also been utilised to improve a deficient pharyngeal swallow (Leow et al., 2007; Palmer et al., 2005).

Due to the confusion and lack of clear standards regarding delivery of a fluid within a therapeutic viscosity range, the National Dysphagia Diet Task Force was formed in the United States of America. In 2002 they published the National Dysphagia Diet (NDD). That recommended labeling diets as thin, nectar-like, honey-like and spoon thick to allow for more accurate compliance with nutritional dysphagia management advice. They also produced viscosity ranges for each of these categories (National-Dysphagia-Task-Force, 2002).

Swallow therapy involves compensatory postural techniques; direct therapy to improve particular aspects of a deficient swallow and indirect therapy to strengthen swallow muscles. Postural techniques are utilised to improve swallow physiology. Techniques available include head back, chin down head rotation and tilt to 1 side and lying down. Each exercise is prescribed for certain disorders observed on VSE. Swallowing maneuvers have been designed to improve particular aspects of the swallow process. These include a supraglottic swallow, super-supraglottic swallow, effortful swallow and the Mendelssohn
maneuver. Strengthening exercises are prescribed for particular dysphagia aetiologies. For instance the Shaker exercise is prescribed to strengthen the muscles in the floor of the mouth to aid upper oesophageal sphincter relaxation. Tongue strengthening exercises have been shown to play a significant role in improving oral phase swallowing (Robbins et al., 2007). For further information on swallow therapy the reader is directed to the following reviews (Logemann, 1997; Logemann, 2007a; Wheeler-Hegland et al., 2009).

Despite significant advances in technology and rehabilitation techniques in dysphagia management there is still a significant lack of evidence-based data available. This is especially the case with swallowing therapies and new diagnostic strategies. Further research into interventions on large populations of specific groups of patients with individual swallowing disorders is required. However, with current management protocols and a multidisciplinary approach, over 85% of patients with oropharyngeal dysphagia can return to full oral intake (Logemann, 2007a).

2.7 Oral components of pressure generation

2.7.1 Anterior oral seal

The anterior oral seal is required for the successful manipulation and swallowing of a liquid bolus. The lips coming into light contact usually create this seal, allowing oral containment of the liquid bolus and generation of negative intra-oral pressure.

Lip position and function is governed by the activity of the surrounding muscles and the underlying bony skeleton. The maxillary and mandibular alveolar ridges and the position of the anterior dentition maintain the sagittal position. The inclination of the dentition can vary greatly due to net equilibrium between forces acting on the teeth (Proffit, 1978). The length of the lip which determines by the depth of the labial sulcus also contributes to lip position (Page and Stranc, 1982).

Competent lips are described as being in light contact at the clinical rest position with almost no voluntary effort required to hold the lips together (Simpson, 1976). Individuals
with incompetent lips require a distinguishable effort in the lower lip and an anterior movement of the tongue to achieve closure of the lips (Gustafsson and Ahlgren, 1975).

Burstone (1967) described lip incompetence in terms of discrepancies between lip length, the dentoalveolar complex and vertical skeletal pattern. Patients with shorter lips and increased vertical skeletal dimensions or large anteroposterior dental discrepancies had increased interlabial gaps and required significantly more effort to close the lips and achieve an anterior oral seal. He also stated the lower lip moved more than the upper lip to achieve a seal. The distance the lips have to close is related to the length of the lips and the skeletal or dentoalveolar height (Burstone, 1967). A study used EMG of the perioral musculature and cephalometric values to investigate the relationship between lip posture and perioral muscle activity. It showed that subjects with incompetent lips required greater perioral muscle activity to achieve lip closure. They also had greater lower anterior face height, high mandibular plane angle, abnormal sagittal skeletal jaw relations, and increased lower incisor proclination (Gustafsson and Ahlgren, 1975). Other studies on lip incompetence have also found an association with increased incisor overjet, skeletal base discrepancies proclination of the mandibular incisors (Simpson, 1976; Leonardo et al., 2009).

Several studies have found increased perioral EMG muscle activity in individuals with incompetent lips. Gustafsson and Ahlgren (1975) found that in individuals with incompetent lips, the upper and lower orbicularis oris as well as mentalis muscle activity increased upon lip closure during mastication and during swallowing. Lip competent subjects, however, only had mildly increased mentalis activity. Simpson (1976) investigated individuals with class II division 1 malocclusions (increased maxillary incisor overjet) and found that the mentalis muscle activity increased proportionately with increasing anterior posterior discrepancy between skeletal and dentoalveolar bases, whilst the upper lip had a more passive role. Tosello et al. (1998) found similar results to the others but found no increase in mentalis activity on closure in competent lip patients.

Contraction of the perioral musculature has long been considered as a clinical sign of abnormal lip function (Tosello et al., 1998). In their study looking at perioral activity in swallowing they found that lip incompetent subjects had significantly increased muscle
activity compared to those with competent lips. Though all their lip incompetent participants had increased perioral muscular activity, they were able to swallow satisfactorily. This illustrated the significant adaptive capabilities of the normally functioning perioral musculature and tongue. This is in accordance with Cleall, (1965) and his research on the form and function of deglutition, who concluded that the stomatognathic system has a marked ability to adapt to changes in the local oral environment through the interaction of the tongue mandible and lips.

2.7.2 Lip incontinence

Lip incontinence is the inability of the lips to contain saliva or fluid in the mouth. There is a paucity of literature devoted to the study of lip function. Stranc and Fogel (1984) were unable to find a single study devoted to lip function within the previous 100 years. They recognised 5 main functions of the lips; oral continence, eating, communication, oral access and maintenance of the intra-oral environment.

Oral continence is achieved through the interplay between lip sensory feedbacks, the height of the lip curtain and the strength of the perioral musculature. Disruption of any 1 of these factors causes oral fluid incontinence proportional to the level of disturbance. Several factors, including sulcus depth, sphincter (orbicularis oris) power, lip sensitivity and interlabial distance, have been assessed. Lip sensitivity and oral sphincter strength had the greatest impact on provision of a satisfactory lip seal (Stranc and Fogel, 1984).

There are many other causes of lip incontinence and these incorporate oro-dental and neurological disorders. Oro-dental causes include skeletal and dentoalveolar malocclusions and disorders of tongue function including, altered resting posture, disordered function and congenital or acquired deformities. Anaesthesia or hypoesthesia of the lips, strictures or deficient lip tissue from trauma (especially burns) can result in inability to maintain an anterior lip seal (Meningaud et al., 2006).

Neurological deficits are numerous and include cerebral palsy, Parkinson’s disease, cerebrovascular accidents (stroke), facial paralysis and motor neurone disease (Meningaud et al., 2006). Parkinson’s patients have most difficulty in swallowing related to the oral
phase due to bradykinesia of the oropharyngeal musculature. This particularly affects lip closure and voluntary tongue movement (Bakheit, 2001).

In the case of patients with lip incompetence and normal tongue function, a physiological adaption of the tongue acts to complete the anterior oral seal by thrusting forward to contact the lower lip (Proffit and Sarver, 2006 pages 153-154). Patients with neurogenic dysphagia and muscle weakness have impaired adaptive potential. They have more difficulty managing low-viscosity liquids than higher viscosity. The optimal viscosity of fluids for management of patients with neurogenic dysphagia has not yet been determined (Bakheit, 2001). Management is further hampered by reduced palatability of excessively thickened liquids and reliable non-subjective methods of achieving a desired viscosity in the clinical setting.

2.7.3 Equilibrium and tongue dynamics

Tongue dynamics have been a source of controversy with regard to cause and effect of certain malocclusions. This is especially the case in that of anterior open bite where the upper and lower anterior teeth do not meet on closure. Here transitional (juvenile) tongue thrusting swallowing pattern with inter-dental positioning and increased perioral contraction has been implicated in the aetiology (Proffit and Sarver, 2006).

Equilibrium exists when a body at rest is subjected to forces in various directions but is not accelerated. In other words the sum of all forces is zero. During mastication and swallowing there are large transient forces at play but these are quickly removed and the dentition, within their periodontal ligament fibres and the alveolar bone return to their original position just as quickly (Proffit, 1978).

Proffit’s (1978) landmark paper on the concept of dental equilibrium reviewed the considerable literature on equilibrium published prior to this. Proffit described primary and secondary factors that alter the equilibrium of tooth position. The 4 major primary factors were; 1) Intrinsic forces provided by the tongue and lips; 2) Extrinsic forces such as those found in habits (thumb sucking) or those applied by orthodontic appliances; 3) Forces from dental occlusion and 4) Forces from the periodontal membrane (Proffit, 1978).
Assuming that the lip and tongue alone result in the positional equilibrium is too simplistic. Early studies investigated average tongue and lip pressures during swallowing and at rest found that they varied considerably between individuals and did not correlate with tooth position. It was found that the intra-oral forces generally exceeded those of the lips by several times (see figure 2.5) (Proffit et al., 1964)

![Figure 2.5: Relative ratio of lingual to labial pressures, from Proffit, (1978).](image)

Later, Lear and Moorrees (1969) summed opposing lip and tongue forces, in normal occlusions, over 4 hours and extrapolated this to 24 hours. Again there was still a considerable force imbalance, with tongue forces on the whole, 4x greater than cheek forces (Lear and Moorrees, 1969). A study that related resting labio-lingual pressure to arch form geometry, also failed to find a balance between labio-lingual resting pressures (Brader, 1972). Proffit concluded, therefore, that other forces must be involved in the maintenance of dental equilibrium. He attributed these forces to brief but high intensity occlusal forces and the very low (2-10g) but constant forces of tooth eruption and the periodontal membrane (Proffit, 1978).

It is critical when analysing forces of equilibrium that duration and magnitude of force is considered. To achieve movement in teeth extrinsic forces are required for approximately 6 hours a day (Proffit and Sarver, 2006). This is the critical duration threshold for the
detrimental effects that result from digit sucking habits or beneficial forces such as orthodontic appliances.

The dentition has a remarkable capacity to absorb large forces for short durations due to the periodontal ligament fibres. At present there is no consensus or scientific evidence regarding the minimal force required to instigate orthodontic tooth movement. As well as this, there is no universally accepted standard for optimal force or frequency of application. However, it is generally accepted that minute changes to the stress and strain distribution in the periodontal ligament fibres are required to initiate the process of orthodontic tooth movement (Melsen et al., 2007).

2.7.4 Tongue thrust
The intrinsic forces produced by the tongue and lips are extremely complex and to this day there is controversy as to their effect on equilibrium. An example of this is the tongue thrust phenomenon. In normal swallowing the tip of the tongue rests on the lingual part of the dentoalveolar area and the contraction of the perioral musculature is minimal while the teeth close into momentary contact (figure 2.6 B) (Cleall, 1965). However, in tongue thrust, (also known as transitional, immature or visceral swallowing) there is a forward posturing of the tongue to meet the lower lip, increased perioral muscular contraction and an absence of tooth contact with the tongue in an interdental position (figure 2.6 A) (Tulley, 1969; Cleall, 1965).
In neonates the tongue is relatively large and is located in a forward position for suckling. During this, the tongue lies between the gum pads and assists with the anterior lip seal while the lips compress to achieve a seal around the breast. With the onset of dental eruption the tongue begins to retract and a transitional period follows (Peng et al., 2004). The transition to the adult pattern of swallowing occurs in normal children as early as 3 years of age: however, the majority achieves the adult pattern by 8 years of age, though habits such as digit sucking delay this transition. A large study, with numbers in excess of 1200, that grouped 6, 7, 8, 9 and 10-year-old children, found 52.3%, 52.8%, 38.5%, 41.9% and 34 % respectively displayed tongue thrust swallows (Fletcher et al., 1961). It is important to note that in 10 to 15% of individuals a transitional swallowing type persists into adulthood (Proffit and Sarver, 2006 page 153-154).

With an anterior open bite or large overjet, (often caused by supra threshold extrinsic forces due to digit sucking habits) it is more difficult to seal off the mouth to prevent escape of liquids. This is especially the case with short upper lip length. The development of an anterior tongue thrust to contact the lower lip and seal off the anterior oral cavity is a useful physiological adaption for preventing dysphagia (Proffit and Sarver, 2006 page 153-154).
Tulley (1969) proposed a working clinical classification of tongue thrust. These were; habit, endogenous or innate tongue thrusting, adaptive behaviour and grossly abnormal tongue problems such as macroglossia. He considered that habit and adaptive behaviour were amenable to correction.

It is extremely unlikely that adaptive tongue thrusting swallows could exceed the duration threshold of tooth movement. If we consider a frequency of swallowing at 1000 swallows per day (Lear et al., 1965) and duration of 2 s per swallow (Logemann, 2007b) this equates to approximately 60 minutes of total lingual swallowing force. This is significantly below the 6-hour threshold for tooth movement. However, small forces of long duration are significant. Therefore, permanent alterations to tongue resting posture or lip strength could conceivably play a significant role in dental malocclusion. This would especially be the case in malocclusions with a high risk of relapse, such as class II division 1 patients with a high upper lip line or skeletal base anterior open bite patients. In these, even slight alterations of equilibrium could tip the balance in favour of malocclusion, either as an initial aetiological factor, or post-treatment leading to relapse.

With this in mind, the question remains as to whether tongue thrust swallows are an aetiological or adaptive factor in anterior open bite malocclusions. Patients with anterior open bites frequently present with incompetent lips and mandibles that have rotated away from the maxilla. These patients have also been described as long faced individuals (Cangialosi, 1984). It is of note that anterior open bite patients have similar morphological characteristics to those of individuals with incompetent lips (Simpson, 1976; Gustafsson and Ahlgren, 1975).

It has been theorised that the vertical component of equilibrium produced by tongue thrusting may prevent eruption of the anterior dentition causing anterior open bite. However using pressure transducers, it was found that tongue thrust swallowers actually had a reduced vertical component of tongue force and a similar horizontal component when compared to normal swallowing patients (Wallen, 1974). These results favoured the adaptive rather than causative nature of tongue thrust.
A review of the literature on tongue thrust swallowing prior to 1985 was carried out. It found that tongue thrusting was the rule rather than the exception under the age of 10 years and could find no close links to dental malocclusion. Though it did not interfere with acquisition of correct sibilant speech articulation, speech development was delayed (Lebrun, 1985).

The current consensus is that tongue thrust swallowing is seen in 2 circumstances: Firstly, as part of the normal transitional process to adult swallowing seen in young children with normal occlusions and, secondly, as an adaptive process in individuals of any age with displaced incisors. In the case of increased overjet it occurs often and in the vertical dimension as in anterior open bite it always occurs. A strong argument for an adaptive rather than causative role is the comparison of the anterior open bite malocclusion prevalence versus the prevalence of tongue thrust swallowing. At every age above 6 the number of children with tongue thrust is approximately 10 times greater than those with anterior open bite. (Proffit and Sarver, 2006 page 153-154). Therefore, though every child with an open bite has a tongue thrust swallow, significantly more children with tongue thrust swallowing do not have an open bite malocclusion. Thus it is reasonable to conclude that although an anterior resting position of the tongue may be contributory to malocclusion, the presence of a tongue thrust swallow is not.

2.8 Patterns of tongue movement during swallowing

Our current understanding of patterns of tongue function during swallowing has been hampered by difficulties in imaging and access. Tongue movements are rapid, with the oral phase lasting no more than 200-350 ms (Cleall, 1965; Stone and Shawker, 1986; Shaker et al., 1988). Early attempts at describing tongue function during swallowing relied on direct visualization of partially dentate patients through separated lips (Abd-El-Malek, 1955). Since then much research delivered small pieces of the complex puzzle of tongue function during swallowing. As yet, no single tool has been developed to allow a complete 3-dimensional analysis that captures tongue and bolus movement, muscle activity, coordination and pressure generation. For now, we must rely on extrapolation of many
studies and research methodologies to piece together the complexities of the oral stage of swallowing. A brief description of some of these follows.

Videofluoroscopic imaging, regarded as the gold standard for the study of feeding behaviour (Hiiemae and Palmer, 2003), has been used to describe patterns of tongue movement during swallowing and has the unique advantage of enabling simultaneous visualization of the tongue, jaw, hyoid and bolus during swallowing. A further advantage is the fact that other diagnostic modalities can be concurrently undertaken. These include intra-oral pressure recording and muscle activity through electromyography (EMG) (Shaker et al., 1988; Cook et al., 1989; Dantas et al., 1990). These studies laid the foundation for much of the research into timing and coordination of deglutition. Disadvantages of VFS include radiation exposure, lack of precise tongue surface measurement and the 2 dimensional, postero-anterior or sagittal viewing restrictions. In addition to this, each frame of a swallowing event taken at 30 frames per second spans 33.33 ms. This leads to overlaps when comparing data recorded at a higher frequency such as pressure recording or electromyography.

Increased precision of 2 dimensional tongue surface visualisation was made possible with the adhesion of pellet markers to the dentition and tongue surface (Gay et al., 1994; Hiiemae and Palmer, 2003). Other methodologies that allow precise 2 dimensional tracking of markers relative to fixed reference points include X-ray microbeam and electromagnetic midsagittal articulography (EMMA). X-ray microbeam was developed in the 1970’s as a method to significantly reduce ionising radiation during the tracking of the movement of biological structures (Fujimura et al., 1973). Via gold reference markers, it has been used in several studies to describe tongue surface temporal and spatial motion at various points on the dorsal tongue surface (Tasko et al., 2002; Wilson and Green, 2006; Hamlet, 1989). Its main disadvantage however, is that it requires concurrent analysis such as ultrasound to allow visualization of tongue structure between the reference markers (Hamlet, 1989).

Electromagnetic midsagittal articulography has also been used to trace transducer coils attached to the surface of the tongue. These coils provide excellent spatial and temporal resolution without the hazards of ionizing radiation and, therefore, allow multiple data
collection sessions (Horn et al., 1997; Steele and Van Lieshout, 2009). Though the coils themselves are small, they require adhesion to the tongue surface and their attachment wires are relatively bulky acting as a potential interference to normal tongue function. As with X-ray microbeam, only individual points can be monitored and as yet has only been able to be used with midline recordings.

Ultrasound is another method used to capture tongue movement that does not utilise ionising radiation. Studies have utilised submental sagittal and transverse imaging of the tongue to describe shape and surface contours during swallowing (Hamlet et al., 1988; Stone and Shawker, 1986; Chi-Fishman and Stone, 1996). By generating real time recording of soft tissues and soft tissue air interfaces, it is able to produce clear sagittal images without masking of hard tissues as in VFS. This technology is rapidly advancing with images of increasing detail and resolution made possible due to higher frequency transducers. It too, is limited by 2 dimensional views and requires stable reference points to track the tongue surface. Another major drawback is that any air within the oral cavity results in loss of detail deeper to this air interface. Ultrasound use in swallowing research has been undertaken in 2 modalities. B-mode creates 2-dimensional images of the tongue at 30 fps (30Hz) that can be slowed or paused but fine movements especially of the tongue tip may be lost (Hiiemae and Palmer, 2003). The other method used is M–mode where a time-amplitude diagram is created that allows more precise tracking of a fixed point on the tongue surface through a fixed scan line (Peng et al., 2004). Hand held, direct transducer-skin coupling scanning on the submental region can result in artifacts that lead to inaccuracies of measuring tongue function. The “Cushion Scanning Technique” developed by (Peng et al., 1996), improved intra-individual reliability by achieving a more standardised technique than hand held examination.

Electropalatography has also been used to look at tongue movement and has the significant advantage of allowing a full visualisation of the tongue palate contact area (Chi-Fishman and Stone, 1996). Unfortunately, its major drawback in swallowing research is that it only provides data for actual contact between tongue and palate. Accordingly, much of the detail regarding behaviour before and after actual contact cannot be recorded. Further to this, it is not possible to tell precisely which part of the tongue is responsible for creation of the contact event and contact is obscured by food boluses.
2.9 Intra-oral pressure

Intra-oral pressures are generated during many activities including speech, mastication and swallowing. The study of intra-oral pressure, as it relates to swallowing, is the focus of this study. A major hurdle that has confronted researchers with regard to measurement of these pressures is the relative inaccessibility of the oral cavity. This has been compounded by the size of pressure recording devices and interference with oral physiology. Early studies into pressure recording involved the use of manometers (Kydd, 1956) and strain gauge pressure transducers (Proffit et al., 1964). One of the original studies measuring tongue pressures in swallowing was that of Kydd and Toda (1962) who used pressure transducers placed into an acrylic removable denture.

Another methodology developed to assess intra-oral positive pressure was the Iowa Oral Performance Instrument (IOPI). It is a hand-held single intra-oral air filled bulb, approximately 20 mm x 10 mm x 5 mm, which was connected to a digital pressure recorder. Several researchers have assessed palatal tongue pressures with this device (Pouderoux and Kahrilas, 1995; Robbins et al., 2007; Stierwalt and Youmans, 2007). Its advantages are its low cost, technical simplicity and ability to be used over a wide range of patients and sample sizes. Two examples of its uses were to assess maximal lingual pressure reserve (Robbins et al., 1995) and improvements in strength after rehabilitation (Robbins et al., 2007).

Another device with similar abilities to diagnose grossly weakened tongue muscle function and response to rehabilitation programs is the Tongue Force Measurement System (TOMS) (Robinovitch et al., 1991). These air-filled bulb devices share common shortcomings. They lack precision in placement; they have large sensors and can only record a single site. They are, therefore, not suitable for measurement of sequential aspects of swallowing or regional differences in intra-oral pressure. The Kay PENTAX Swallowing Workstation™ can record multiple pressure transducers and, therefore, multiple intra-oral sites. It accomplishes this via 2 to 3 bulbs (5 mm x 5 mm) attached via an adhesive midline plastic strip (Steele et al., 2010). However, it too lacks precision in
placement of the bulbs that are of a relatively large size. A device currently under
development is the Madison Oral Strengthening Therapeutic device (MOST). It too has
multiple sensors and due to a custom-fit mouthpiece, the problem of reproducible
placement is addressed. However, it is hampered by the fact it can only measure positive
pressure (Hewitt et al., 2008).

Chiba et al. (2003) measured tongue pressures using an orthodontic transpalatal arch with
a pressure sensor that could be moved to various locations in the palate. However, this
only measured the midline and did not reach the anterior palate.

One of the drawbacks with intra-oral pressure measurement to date has been the inability
to achieve an understanding of sequential tongue palate contact over the entire palate.
Most studies due to methodological limitation have been restricted to the midline and have
focused on positive pressures only. In an effort to increase the accuracy of the regional
distribution of linguo-palatal pressures, Ono et al. (2004) fabricated an acrylic appliance
that was custom fitted to the hard palate and contained 7 pressure sensors. This gave clear
information about the order, magnitude, and direction of linguo-palatal forces over the
hard palate during water swallowing. They found that coordination of the tongue
contacting the hard palate typically showed a sequential pattern from the anterior-median,
anterior lateral, postero-lateral and postero-median respectively. However, their device
was only able to measure positive pressures and as such failed to give a complete
description of intra-oral pressures generated during swallowing.

Subsequently, Hori et al. (2009), have developed an extremely thin (0.1 mm) T shaped
array of 5 positive pressure sensors. These are adhered to the palate and are able to record
simultaneous positive pressure readings. Manufactured in 3 sizes small, medium and large
it is suitable for large-scale use as a diagnostic and rehabilitative tool but currently
pressure readings are not as accurate as the device designed by Ono et al. (2004). As
previously stated, the major restriction of an intra-oral positive pressure analysis was that
coordinative data could only be applied to bolus clearance rather than total effects on bolus
transit.
2.10 Pressure flow dynamics and the bolus

Research on positive intra-oral pressure has shown that swallowing pressures are sub maximal when compared to maximal isometric pressure generation tasks. Robbins et al. (1995) and Nicosia et al. (2000) both showed that although maximal pressures declined with age, the mean pressures involved in swallowing did not change. This emphasised the fact that pressures generated to transport a liquid bolus fall well below the lingual strength reserve, even in healthy elderly populations (Robbins et al., 1995; Nicosia et al., 2000; Youmans et al., 2009).

The bolus itself consists of a head and tail as it moves through the various stages of swallowing (Lund, 1976). Research into swallowing patterns such as that by Shaker et al. (1988) and Cook et al. (1989) identified the need for a thorough understanding of normal swallowing behaviour. Their discovery of ‘Incisor’ and ‘Dipper’ swallowing variants had significant bearing on normal swallowing analysis factors such as timing of onset and the fact that various types of normal swallowing modalities exist.

In the review by Dodds et al. (1990), the radiographic positioning of the liquid bolus was described using sagittal and coronal views of the oral cavity. In the oral phase of the swallow, the bolus was located along the midline groove of the tongue in a spoon-like depression of the mid tongue. Concurrently the posterior tongue elevated and a seal was formed with the soft palate to prevent premature entry of the bolus into the unprepared pharynx. The anterior 2/3 of the tongue was next described as elevating and rolling back posteriorly in a piston-like manner, effectively forcing the bolus into the oropharynx.

Researching intra-oral pressure and bolus flow dynamics, Shaker et al. (1988) used 2 high-fidelity manometric strain gauges to focus on the tongue pressure during discrete barium swallows. Significantly, they showed that negative pressures recorded at the mid tongue coincided with movement of the tongue away from the palate (Shaker et al., 1988). Additionally, they noted that a major positive deflection coincided with the instant of tongue to palate closure. Concerning bolus flow, they described that the bolus head passed ahead of the terminal peristaltic wave, reaching the pharynx 0.2-0.3 s earlier than the tail.
They also noted that the head of a large bolus arrived earlier than that of a smaller bolus and that the bolus tail was cleared by the stereotyped positive pressure peristaltic wave. Cook et al. (1989) undertook further similar research that compared concurrent manometric midline positive pressure waves to videofluoroscopic images of tongue and bolus movement. They showed that the passage of the bolus tail and the upstroke of the peristaltic pressure wave occur practically coincidentally, with mean values of 0.01 s. The sequential diagram of liquid bolus flow relative to tongue palate contact, taken from Matsuo and Palmer, (2008), clearly illustrates the relative positions of bolus head and tail during the posteriorly directed peristaltic wave (see figure 2.7).

Figure 2.7: Sequence derived from still frames during videofluoroscopic analysis of liquid swallows. The bolus (grey) movement is depicted relative to lingual (white) and palatal (black) contact (A) represents end of preparatory stage with the tip of the tongue contacting the incisors and the base of the tongue elevated preventing bolus entry into the pharynx. B) and C) represent the propulsive phase with the base of the tongue dropping and the bolus head entering the pharynx. Taken from Matsuo and Palmer, (2008)

The effects of negative pressure on the bolus head and body have not been reported thus far. Whether this is involved with bolus capture and positioning or actual initiation of the head of the bolus remains to be seen. A study using electropalatography, observed that there was significantly less linguopalatal contact in sequential liquid swallowing than in discrete liquid swallowing (Chi-Fishman et al., 1998). Based on this observation, one could reasonably surmise that the positive pressure terminal wave seen in the clearing peristaltic wave may not be required for sequentially swallowed liquid boluses and that negative pressure may play a more significant role. Future research on absolute pressure in this area is warranted.
2.11 Swallowing variability

2.11.1 Inter-subject variability

That considerable inter-individual variation exists between swallows has been noted for some time. In their paper, Shaker et al. (1988) were able to describe that a wide range of inter-individual pressure profiles exist within a normal appearing bolus transit. Making use of videofluoroscopy (VFS) to analyse patterns relating to the onset of swallowing, Dodds et al. (1989) described that 2 distinct types of normal swallowing occurred. They termed these “tipper and dipper type” swallows. In the more common tipper, the swallow was initiated with the tongue tip on the incisors, whereas in the dipper swallow, the tongue tip dipped below the bolus before lifting it up and back. The remaining phases of the swallow were noted to be identical. The result of this was that duration of swallowing was approximately 0.5 s longer in the dipper swallows (Dodds et al., 1989). Other researchers to describe this significant variation include Gay et al. (1994). They described significant temporal and spatial variability in VFS tracking pellet markers in water swallows. They suggested the existence of individual adaptive programming strategies in the development of swallowing movements during maturation from the innate infantile feeding reflex. Tasko et al. (2002) investigated X-ray microbeam pellet trajectories in water swallows on 12 subjects. They too noted a similar marked variation between subjects. They commented that this variation was of such an extent that quantitative description of tongue kinematics proved very difficult. They qualified this stating that most variation was at the tongue tip with more similarity noted in the more caudal parts of the tongue.

Concerning mean and maximal pressure, Shaker et al. (1988) found large inter-subject pressure variations in their manometric midline swallowing study. Youmans and Stierwalt (2006) also analysed mean swallowing pressure and found high variability between individuals in the anterior palate with a large range of pressures and large standard deviation. Maximal tongue grooving at the midline has been compared using lateral tongue markers as a reference (Hamlet, 1989). It was noted that there were marked individual differences in the degree of tongue grooving exhibited, with some subjects showing no grooving at all. Significant inter-individual variation was also reported by Kennedy et al. (2010), who investigated anterior mid and posterior palatal midline absolute pressures and
found a similarly large range of pressure patterns and means generated between individuals.

Inter-subject similarity on the other hand, has been less obvious. Chi-Fishman et al. (1988) noted only small inter-subject variation in contact patterns on EPG. Other kinematic studies by Tasko et al. (2002) and Wilson and Green (2006) showed that inter-subject variation decreases in the later part of the swallow. So-called invariant aspects of swallowing have been described. This relates to the serial anchoring of the anterior tongue to the palate with a caudally directed, sequential contact of tongue to palate (Cook et al., 1989; Kahrilas et al., 1993; Ono et al., 2004). It is worth noting that this similarity is regarding the peristaltic phase of the swallow based on the clearing contact between the tongue and hard palate.

Recognising the difficulty in quantitative analysis of significantly different pressures and profiles produced by each individual Kieser et al. (2011) proposed a heuristic classification of 3 basic types of swallow according to their basic pressure profiles. These were the “type I squeezer, type II slider and type III slapper”. Although participant numbers were low, they highlighted the significant problems faced in attempting to define a normal swallow.

2.11.2 Intra-subject variability

Though there is considerable literature that suggests inter-individual variation, it is noteworthy that research analysing intra-subject variability has shown the opposite trend (Ono et al., 2004; Peng et al., 2007; Kennedy et al., 2010). In Kennedy and co-workers’ research, remarkable similarity was observed within individuals over 5 consecutive days. This was evident in peak pressures, timing, and polarity. The pressure profiles were so similar that they were able to identify each individual’s signature swallow irrespective of the day they were recorded. In the case of varying bolus consistency, Youmans and Stierwalt (2006) found that despite corresponding increases in pressure with increasing viscosity, the underlying pattern of low-pressure swallowers and high-pressure swallowers was conserved.

When considering this apparent intra-individual similarity, it is important to note that this was only at similar regions of the tongue. Shaker et al. (1988) reported significant regional
variations of tongue function. They found that the tongue tip presented a monophasic or biphasic pressure profile whilst the mid tongue produced a spike and dome appearance. This clearly demonstrated varied pressure behaviour at different locations in the oral cavity. (Shaker et al., 1988) Research on midline pellet movements by Tasko et al. (2002), Wilson and Green (2006) and Steele and Van Lieshout (2009) all revealed that movement patterns of the anterior tongue regions were distinct from those of the posterior tongue. Essentially they noted more rostro-caudal pattern anteriorly and a more vertical movement pattern posteriorly. Anatomical considerations most likely explain these phenomena.

2.12 Summary

Despite considerable research, there remains a lack of understanding regarding the precise behaviour of the tongue during the oral phase of swallowing. This is largely due to the significant difficulty in access and visualization of the tongue during function. Recent reviews have highlighted the fact that the tongue is an exquisitely intricate, highly mobile organ capable of precise and rapid movements during the processes of speech and bolus manipulation e.g. (Youmans and Stierwalt, 2006; Gilbert et al., 2007; Stierwalt and Youmans, 2007; Felton et al., 2007). However, there still remains a limited understanding with respect to the precise mechanisms of bolus transfer through the oral cavity during the oral phase of deglutition.

Intra-oral lingual swallowing pressures have been shown to be highly variable across but not within individuals with respect to absolute values (Pelletier and Dhanaraj, 2006) and pressure patterns (Kennedy et al., 2010; Kieser et al., 2011). Controversy surrounds the effects of altered bolus viscosity on intra-oral pressures. While some researchers have demonstrated increased pressure with increasing viscosity (Shaker et al., 1988; Miller and Watkin, 1996; Nicosia and Robbins, 2001), others have found no difference (Butler et al., 2004; Steele et al., 2010). Furthermore, the majority of intra-oral pressure studies to date have concentrated on the midline and have measured positive, rather than absolute pressure.
The present study continues earlier research that has led to the development of a reliable and robust tool for measurement of absolute intra-oral pressure, something that has not been utilised by other researchers to date (Kieser et al., 2008; Kennedy et al., 2010). Subsequent research has focused on the intra-oral pressures and tongue dynamics during swallowing along the midline (Raniga, 2009). The present study continues along these lines, but additionally analyses the pressure patterns developed along the lateral margins of the tongue-palate interface, hence allowing a partial 3 dimensional appraisal of pressure patterns across 7 regions of the palate.

The main objectives of this study are; firstly, to explore whether there is a common intra-oral pressure pattern underlying the marked inter-individual pressure variation previously recognised; and secondly, to investigate the effects of increasing viscosity on the absolute intra-oral pressure developed during the propulsion of a fixed-volume bolus through the oral cavity.
3 Methodology

3.1 Purpose

This study was a prospective, descriptive and quantitative evaluation of absolute intra-oral pressures induced by 2 experimental interventions. Firstly, the patterns and inter-individual variation between water swallows and a mildly flavoured liquid of negligibly different viscosity were investigated. Secondly, the effects of increased of viscosity on absolute intra-oral pressure and dynamics were investigated. For this study, an established intra-oral pressure recording system consisting of an artificial palatal appliance was used, with 7 pressure sensors to measure simultaneous, absolute pressures in the oral cavity. These were the sagittal midline of the anterior, middle, posterior and the anterior and posterior on each of the lateral aspects of the hard palate.

3.1.1 Principal research questions

1. Is there a universal pressure pattern to the oral phase of the swallow underlying the significant inter-individual variation that exists?
2. What are the effects of viscosity on the nature of absolute intra-oral pressure changes within and between individuals?

3.1.2 Research Hypotheses

1. That a defined inter-individual pattern of absolute intra-oral pressure underlies the marked variation known to exist within the oral phase of swallowing.
2. That both inter- and intra-individual patterns of oral pressure generated during discrete liquid swallowing will change with increasing viscosity.
3.2 Study design

3.2.1 Ethical approval
The University of Otago Ethics Committee has granted ethical approval. All participants provided signed consent after reading the information sheet provided.

3.2.2 Sample
A convenience sample of 10 healthy adult volunteers was selected from the post-graduate and under-graduate students at the University of Otago, Faculty of Dentistry. The sample was equally divided by gender with 5 males and 5 female participants and was aged between 21-41 years. The inclusion and exclusion criteria for selection of subjects are detailed below. Due to small sample size of 10 the decision was made not to analyse results on the basis of gender. Due to issues with poor palatability of thickened water affecting intra-oral pressure recording, participants were asked to describe each bolus as unpleasant, neither pleasant nor unpleasant, or pleasant. They were also questioned regarding their medical history status.

3.2.3 Inclusion Criteria
All participants had complete dentition with the exception of third molars. They all had class 1 sagittal molar occlusions as defined by Edward Angle (Angle, 1899) and acceptable incisal overbite and overjet measurements as defined by (Freer and Freer, 1999). These were an overjet of 2-4 mm on a class 1 skeletal base with an overbite of 3-4 mm upper incisal overlap of the lower incisors. All participants had competent lips as assessed by absence of mentalis contraction at rest, on complete lip closure. All participants had excellent general health, with no history of muscular disease, swallowing disorders or speech impediment. All Participants were questioned regarding medication use and temporomandibular joint (TMJ) dysfunction.

3.2.4 Exclusion criteria
As the aims of this experiment were to analyse intra-oral pressures in normal healthy individuals, participants were excluded if they were taking any medications with side effects listed as xerostomia or muscular interference. Similarly, those with lip
incompetence at rest, severe skeletal base discrepancy, prior dental extraction, TMJ dysfunction, and respiratory disease were excluded.

3.3 Base-plate design and fabrication

(Gould and Picton, 1963), found that accurate measurement of mean peak forces was unaffected if protrusion of recording devices from the hard palate was less than 1 mm. It has also been shown that a rigid surface is necessary to prevent flexion of the foil strain gauges and prevent artifactual readings (Kieser et al., 2008). To conform to these parameters; a rigid, custom-fit, cast chrome-cobalt base-plate was fabricated for each participant. This was similar to the proven design of that used by Kieser et al. (2008). Variations to their design included use of cast clasps engaging undercuts in the molar and premolar region instead of the buccal surface wrap around design. Palatal rugae were included on the base-plate to minimise physiological disturbance of tongue function and possible forward posturing as reported by (Reinicke et al. 1998). By restricting the base plate thickness to 0.3 mm and factoring in the 0.5 mm thickness of the pressure transducers, a total thickness of less than 1 mm was achieved.

3.3.1 Chrome-Cobalt Base-plate

Primary impressions of upper and lower teeth were taken for all 10 participants. To ensure an accurate reproduction and subsequent custom fit, several important steps had to be carried out. First, an impression tray of suitable size was selected. This minimised participant discomfort and ensured that the entire dentition and hard palate could be accommodated without encroaching onto the soft palate or buccal sulcus. The trays were coated in universal VPS (vinyl polysiloxane) adhesive (GC America Inc, USA) and allowed to dry. Subsequently, a heavy body base and catalyst vinyl polysiloxane impression putty material (Express™ STD Firmer Set, 3M ESPE, USA) was mixed according to instructions. This was placed in the impression tray, followed immediately by a layer of polyethylene cling wrap (GLAD® Cling Wrap, Clorox Pty Ltd, Australia) to cover the entire tray and impression material. This step was to minimise moisture contamination from the mouth. To record the dentition and hard palate, the tray was firmly
seated in the mouth for 10 s then removed. This stage created an accurately fitting secondary impression space to allow for the visco-elastic recovery of the light body impression material to follow. This step using the heavy body vinyl polysiloxane impression base removed the need for a premade custom tray and a subsequent participant visit. After removing the cling film, light-body, hydrophilic polyvinyl siloxane (Monophase Examix™ NDS, GC America Inc, USA) was injected into the initial impression space, effectively taking the secondary impression. The next step was registering the bite in maximum intercuspation using regular set vinyl polysiloxane (Peppermint Snap Clear Bite, Discuss Dental Inc, USA). This ensured that base-plate fabrication could be achieved without occlusal interferences.

The Impressions were next cast in Type IV dental stone (GC Fujirock EP, Belgium) to allow fabrication of the cast chrome-cobalt base-plate. Casting wax (0.3 mm, Bego, Germany) was used for the base plate and profile wax (0.6 mm, Bego, Germany) was used to create the housings and channels for the transducers and the attached wires). Retention was achieved by waxing-up clasps to engage undercuts in the buccal surface of the dentition. Care was taken to prevent occlusal interferences in maximal intercuspation and during excursive movements.

The refractory wax model was then sprued and cast in chrome-cobalt alloy (Wiront, Bego, Germany) as per manufacturer’s directions. The thickness of the chrome-cobalt base-plate was kept to a maximum of 0.5 mm on palatal surfaces. Following manufacture, a try-in was performed to ensure a comfortable fit free from occlusal interferences. If any occlusal contact surfaces were noted, they were subsequently removed with a high-speed dental bur out of the mouth.

### 3.3.2 Pressure transducers

Seven miniature stainless-steel diaphragm pressure transducers (type 105s, Precision Measurement Company, Michigan, USA) were used to record absolute intra-oral pressure. The transducers were designed to record +/- 420 kilopascals (kPa). They were used due to their exceptionally small dimensions with a thickness of only 0.508 mm and diameter of 2.67 mm. These dimensions, coupled with that of the base-plate, enabled a total palatal
protrusion of 0.8 mm total well under the 1 mm maximum recommended by Gould and Picton (1963). Measurement of intra-oral pressure for this study is based on the assumption that cheeks and lips exert a hydrostatic pressure that is transmitted in all directions through the fluid and not a solid perpendicular force (Lindeman and Moore, 1990; Shellhart et al., 1997). Pressure transducers incorporating a diaphragm respond to pressure, not to a perpendicular force, as is the case in strain gauges or pressure load cells. As a result, diaphragm-based pressure transducers were selected as the most accurate means for measurement of absolute intra-oral pressure.

### 3.3.3 Sensor Location

The pressure transducers were located in standardised positions. Three sensors were placed in the sagittal midline of the oral cavity. These were at the incisive papilla, deepest aspect of the hard palate, and 2 mm anterior to the distal finishing line of the base-plate. They were numbered 1, 2 and 3 respectively. Four sensors were located on the lateral hard palate the mid point of the left and right canines and first molars at the level of the palatal gingival margin. They were numbered 4 and 5 at the left anterior and posterior palate, and 6 and 7 at the right anterior and posterior palate respectively (See figure 3.1). The finishing line of the base-plate was set at the junction between the hard and soft palate.
The sensors and their corresponding wires were then secured into their recessed housings using pink dental wax (Kemdent, UK). It was important that the sensors were placed in maximal contact with the base-plate to allow equalisation of base-plate and transducer temperature with the base-plate acting as a thermal sink (see figure 3.1 B). This was found to reduce fluctuation in transducer temperature and, therefore, voltage drift due to thermal expansion and contraction of the stainless steel diaphragm. The transducer wires were placed into their respective channels cast into the chrome-cobalt base-plate and subsequently retained in pink dental wax (Kemdent, UK). The wires were finally secured with dental floss, to the left buccal aspect of the retention clasps to minimise oral and labial interference. They finally exited on the left side of the mouth at the right labial commisure (Figure 3.2).
Figure 3.2: Chrome-cobalt base-plate with retentive clasps. Ready for use with transducers waxed in and wires tied

The sensors located on the palatal vault represented pressure fluctuations of the anterior, middle, and posterior palate. The data from the lateral palatal pressure sensors were to enable assessment of symmetry and absolute pressure generated by the lateral aspects of the tongue during swallowing.

3.4 Submental surface electromyography (sEMG)

Surface electromyography (sEMG) has been used to measure timing and amplitude of muscular activation events in many swallowing studies (Cook et al., 1989; Dantas et al., 1990; Perlman et al., 1999; Ding et al., 2002; Vaiman et al., 2004; Crary, 2006; Huckabee and Steele, 2006; Taniguchi et al., 2008). It has also been utilised as a biofeedback strategy in the management of dysphagia (Huckabee and Cannito, 1999; Crary et al., 2004) and to estimate swallowing function (Huckabee et al., 2005). Throughout these studies, it has been shown to be a reliable, safe and importantly, non-invasive technique. Further to this, it is readily learned by clinicians, is relatively inexpensive, and can be used concurrently with a wide range of other diagnostic modalities and clinical interventions. Additionally, it provides a composite description of submental muscle group activity, as it takes only a single muscle within this group to create an electric signal capable of being picked up by
the surface electrodes. Shaker et al. (1988) showed that submental muscles stabilise the floor of the mouth in combination with extrinsic muscles to provide a firm base for tongue pressure generation.

A caveat to this advantage, is the fact that submental sEMG is an imprecise tool for specific muscle identification, as it cannot differentiate between individual muscle activation (Ding et al., 2002). The major muscles picked up in submental sEMG recording are the geniohyoid, anterior belly of digastric and mylohyoid with only minimal input from the genioglossus (Palmer et al., 1999). Two recent studies assessed the correlation between lingual palatal pressures and submental sEMG (Yoshida et al., 2007; Lenius et al., 2009). It was found that during maximal tongue press tasks there was a poor correlation between sEMG and lingual palatal forces measured. It was, however, acknowledged that these command tasks were not physiologically representative of the full range of muscles activated during swallowing.

Submental sEMG has been shown to have very high inter-individual variations in amplitude and duration (Ding et al., 2002; Vaiman et al., 2004). Other studies have shown considerable inter-individual variation in timing of muscle activation patterns (Perlman et al., 1999; Crary, 2006). Many factors contribute to this variation between individuals. Anatomical issues such as depth and size of muscles relative to the electrode position create significant variation. A major technological source of variation is skin electrode impedance. This occurs when impedance noise arises from resistance between the electrode and poorly prepared skin. This can be reduced by careful preparation via removal of surface hair, dead skin cells and skin oil by shaving (if required) and/or vigorous rubbing with water-moistened isopropyl alcohol wipes (Vaiman et al., 2004). Two key findings suggest that submental sEMG is not suitable to measure initial stages of tongue force in swallowing. Firstly, genioglossus has been reported to have only small input on submental sEMG activity (Palmer et al., 2008) and secondly, the anterior portion of the tongue is almost entirely composed of intrinsic muscle with only minimal genioglossus insertion (Kieser et al., 2011). This is further supported by the work of Vaiman et al. (2004) who found that orbicularis oris sEMG was more representative of the initial stages of the oral phase of the swallow and that submental sEMG was associated with the late oral stage of swallowing. In an attempt to correlate submental sEMG signals to
biomechanical events, Crary, (2006) simultaneously recorded submental sEMG and VFS at 30 fps. They were able to demonstrate that the swallowing event most highly associated with the submental sEMG signal was hyoid movement with laryngeal movement also closely related. This is in keeping with results reported by Ding et al. (2002).

Many studies have used sEMG as a measure for recording initiation and termination of swallowing. Ding et al (2002) studied 5 muscle groups in 20 participants and found that the orbicularis muscles initiated the swallow followed by masseter, submental and finally infrahyoid muscle groups. The same findings regarding initiation were also reported by a much larger study of 300 adults by Vaiman et al (2004). They concluded that orbicularis oris muscles and masseter were associated with initial stages of swallowing with masseter and submental in the later stages of the oral phase carrying through with the infrahyoid muscle group in the pharyngeal stage. As a result sEMG in this study was used primarily as a link between previous studies utilising videofluoroscopy and initiation of swallowing timing events rather than as a precise measure of lingual muscle activation.

Crary et al. (2007) recognised that there were limited data available on the validity and reliability of sEMG data interpretation with respect to swallowing characteristics. Their findings suggested that the graphic record of submental sEMG was valid and reliable with respect to identifying swallowing movements. Not surprisingly they also found an increase in accuracy with experience. Within the study they found it was more likely to misinterpret a swallow event as non-swallow movement (false negative) than to incorrectly identify non-swallow movement as a swallow (false positive).

Of importance, however, is that within a study it can be assumed that the same muscle group can be relied upon to accurately measure onset and peak and can be used to draw conclusions regarding effects on swallowing variable interventions with respect to timing. Perlman et al. (1999), using intramuscular and submental sEMG, specifically assessed timing and activation patterns during swallowing. They noted considerable inter-subject variability existed but importantly high intra-subject agreement was found.

Three surface electromyography sensors were placed to allow timing comparisons to be made between pressure events and submental EMG activity. This also gave the potential to link pressure events recorded in this study to bolus behaviour described by others who
used concurrent sEMG and videofluoroscopy to analyse temporal relationships of bolus flow during swallowing (Shaker et al., 1988; Cook et al., 1989; Crary, 2006; Taniguchi et al., 2008). We chose to place the electrodes to the right side of midline to maximise the recordings from the submental and suprahypoid muscle groups.

It has been shown that rectified and filtered signals are more convenient for analysis than raw recordings (Vaiman et al., 2004). We first utilised a high pass filter set at 10 Hz to eliminate drift from baseline. Rectification involves converting the bipolar raw EMG signal to a unipolar signal for analysis. This was achieved by using a full wave rectification by calculating the absolute value integral with a time constant decay of 0.1 s. This step made peak EMG activity and initiation of swallowing much easier to identify in line with Vaiman’s recommendation whilst conserving all EMG activity for analysis.

The submental sEMG signals were recorded using 3 MLA 1010 disposable Ag/AgCl ECG electrodes. (AD Instruments Pty Ltd, NSW, Australia). These are 10 mm diameter electrodes with a 30 mm diameter adhesive pad allowing an inter-electrode distance of 20 mm when placed side by side. They were connected using MLA 0310 (AD Instruments Pty Ltd, NSW, Australia) 1.8 m unshielded lead wires with 4 mm diameter ‘snap-on’ connectors. (10 mm diameter) were used to record submental sEMG signals. Two electrodes were placed on the right side of the midline with the first electrode placed caudally to the mandibular symphysis. Exact location was palpated to ensure that the electrode was placed over contractile muscle and not bone. The second sensor was placed immediately caudal to this, ensuring that the inter-electrode distance was 20 mm (see figure 3.3 A). The third grounding electrode was placed on the right forehead in the region with the least muscular contraction (see figure 3.3 B). This step was found to be essential to minimise signal interference and background noise. To minimise skin-electrode impedance, all skin surfaces were shaved if facial hair was observed. They were then prepared using Briemarpak® 70% isopropyl alcohol swabs (Briemar Nominees Pty Ltd, Australia) to remove skin oil and dead skin as well as to improve ion flow and, therefore, signal conduction (Vaiman et al., 2004). Finally the electrodes were kept in close approximation to the subcutaneous muscles by taping under the chin using 25.4 mm hypoallergenic paper tape (Micropore™ Tape 1530-1, 3M, USA).
3.5 Recording set up and safety

Recording was undertaken with a PowerLab® ML 785 data acquisition system, PowerLab® ML 228 8-channel Octal Bridge Amp, PowerLab® ML 138, 8-channel Octal Bio Amp (ADInstruments Pty Ltd, NSW, Australia) and personal computer (HP Presario 2548 Laptop Computer). The software used to record and analyse data included LabChart® Reader 7.0.2 for Windows, utilising the Chart®, Scope® and Zoom® functions. (ADInstruments Pty Ltd, NSW, Australia), Microsoft Office Excel® was used for data manipulation with Microsoft XP Professional® as the operating system. Due to safety requirements the recording hardware was sealed in a “Perspex” (PMMA) box designed and created by Emtech Laboratories, University of Otago (see figure 3.4). To isolate the participants from a live power source, a 12-volt gel-cell battery was used to provide power to the recording equipment and the recording PC was powered by its internal battery. Following each recording session the testing equipment was connected to the 240-volt mains supply to recharge the batteries. As an added safety precaution the unit was not able to record whilst connected to the mains supply.
3.6 Data Recording

Each pressure transducer produced an analogue voltage signal; the amplitude of which was altered continuously by pressure changes or mechanical interference. The raw signal from each of the 7 pressure transducers was amplified by the PowerLab® ML 228 8-channel Octal Bridge Amp; a software-controlled, non-isolated, low-noise bridge amplifier suitable for use with strain gauges, force and pressure transducers. The raw signal from the sEMG electrodes was amplified by the PowerLab® ML 138, 8-channel Octal Bio Amp; designed to electrically isolate differential AC input with a shared ground connector. The signals from these inputs were subsequently recorded using the 8-channel PowerLab® ML 785 data acquisition system. The analogue input signals from the ECG electrodes and pressure transducers were then conditioned by filtering and amplification. These conditioned
signals are then sampled at regular intervals and converted from analogue to digital form suitable for transfer to the computer attached via USB cable (see figure 3.5). This raw digital data was then recorded by the LabChart® 7.0.2 software (ADInstruments Pty Ltd, NSW, Australia) and displayed as 8 channels. Channels 1-7 were pressure-time fluctuations for the pressure transducers, and channel 8 as voltage-time fluctuation for the EMG electrodes. The data were recorded at 1000 Hz and for the pressure transducers were converted from millivolts (mV) to kilopascals (kPa) via a standardised calibration procedure. The EMG data were unchanged from millivolts.

![Figure 3.5: Pressure transducer signal conditioning and data recording.](image)

### 3.7 Calibration

As previously stated the calibration procedure converts the pressure transducer data from mV to kPa. It also ensures that the pressure displayed in the software is an accurate representation of the actual pressures measured. To enable this, the pressure transducers are left attached to the recording equipment for 15 minutes to ensure that the chrome cobalt plates and transducers have thermally equalised. This prevents thermal drifting of the signal caused by thermal dimensional changes of the stainless steel diaphragm. Fifteen
minutes was found to be the time required for thermal equalisation in our pilot studies. (see figure 3.6)

![Figure 3.6: Time until equalisation of pressure transducer thermal drift](image)

Following this warm up period, the transducers were placed in a custom-machined, o-ring sealed, brass container (Emtech Laboratories, University of Otago). This chamber also consisted of sealed cable glands, an inflow pressure connector, and a pressure-releasing valve. It also had 2 analogue pressure gauges, 1 positive (0 to 100 kPa) and 1 negative (0 to -100 kPa), each being attached to a 2-way air-flow valve (see figure 3.7A). Inside the container, the transducers were zeroed to atmospheric pressure using the LabChart® software. A piece of cardboard of a diameter slightly smaller than the chamber was placed over the recording base-plate to ensure that the transducers were not in contact with the cable. After zeroing, the chamber was sealed and tightened using a spanner. Positive pressure was introduced to the chamber by a regulated flow of Nitrogen gas into the pressure connection. This inflow was monitored on the positive pressure valve using the regulator on the Nitrogen bottle and the vent valve on the chamber to allow a continuous flow of gas through the system maintaining a constant pressure of 50 kPa. The pressure was then released to return the chamber to atmospheric pressure and a unit conversion was
undertaken on the software to convert the raw transducer mV readings to a known 0 kPa and 50 kPa for each of the 7 transducers. The transducers were then re-zeroed and the testing appliance was removed from the chamber and prepared for placing in the subject’s mouth. During the pilot study, positive and negative linearity of the pressure transducers was confirmed by attachment of a vacuum pump (VP3 easy, Ivoclar Vivadent AG, Germany) (see figure 3.7).

![A) Sealed brass calibration chamber and pressure releasing valve with analogue positive and negative pressure gauges; B) VP3 Easy vacuum pump.](image)

After zeroing at atmospheric pressure a constant positive pressure of +50 kPa was introduced. Following a return to atmospheric pressure, a pressure of -50 kPa was achieved with the aid of the vacuum pump and the pressure-releasing valve. The results confirmed the linearity of the transducers through positive and negative pressures (see figure 3.8).
Figure 3.8: Confirmation of positive to negative 50 kPa linear calibration test results.

3.8 Liquid preparation

3.8.1 Bolus parameters

Viscosity and volume both have effects on swallowing dynamics (Dantas et al., 1990; Sugita et al., 2006; Pouderoux and Kahrilas, 1995; Pelletier and Dhanaraj, 2006). As a result the bolus volume was kept constant. There is a growing body of data on water swallowing, gathered by previous researchers in this facility. To allow comparison of these data and establish a larger body of normative data the decision was made to keep the volumes of the swallows at 10ml. To maximise inter-experimental comparison, the water and Mizone® was offered in a standard plastic cup as per previous protocols. All liquids were measured with a 10 ml syringe and the subjects self-administered the viscous liquids orally by syringe.
To allow comparison of results to other studies on the effects of viscosity on oropharyngeal aspects of swallowing, it was decided to use the standardised USA fluid viscosity scale as defined by the National Dysphagia Task Force. A comparison table from other national scales compiled by Atherton et al. (2007) is included for reference; see figure (3.9). The viscosity of the liquids used in this research was tested at the same liquid temperature and strain rate as that used with the USA fluid viscosity scale, which was 25°C and a strain rate of 50 s⁻¹ (National-Dysphagia-Task-Force, 2002).

<table>
<thead>
<tr>
<th>Australian fluid viscosity scale</th>
<th>USA fluid viscosity scale</th>
<th>UK fluid viscosity scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>Thin 1–50 cP</td>
<td>Thin fluid</td>
</tr>
<tr>
<td>Level 150—Mildly thick</td>
<td>Nectar-like thick fluids 51–350 cP</td>
<td>Naturally thick fluid</td>
</tr>
<tr>
<td>Level 400—Moderately thick</td>
<td>Honey-like thick fluids 351–1750 cP</td>
<td>Thickened fluid—Stage 1</td>
</tr>
<tr>
<td>Level 900—Extremely thick</td>
<td>Spoon-thick fluids &gt;1750 cP</td>
<td>Thickened fluid—Stage 2</td>
</tr>
</tbody>
</table>

Figure 3.9 Comparison between; the Australian fluid texture modification scale, the National Dysphagia Diet (US) and the UK (adult) texture classification systems for individuals with dysphagia (Atherton et al., 2007).

A wide variation in viscosity within the consistency categories (thin, nectar-thick, and honey-thick) has been found between commercially available food thickeners (Garcia et al., 2005). As a result, the same brand of thickening agent (Resource® Thicken Up® Nestlé S.A., Vevey, Switzerland) was chosen for all experiments. This is a commercially available cornstarch-based thickening agent utilised in the management of dysphagia. Preparation procedure, serving temperature and type of liquid to be thickened all have a profound influence on final viscosity (Garcia et al., 2005; Pelletier, 1997). Cornstarch gels are composed of starch granules, which absorb water. Their subsequent structure is dependent on the formation of hydrogen bonds within a continuous viscous matrix. The water then becomes a composite non-Newtonian fluid with rheological properties dependant on the interactions between the starch granules and the continuous viscous matrix (Dewar and Joyce, 2006).

Non-Newtonian fluids are susceptible to yield stress (Steele et al., 2003). To minimise this effect the thickened liquids were stirred for 10 s prior to drawing up in the syringe and subsequent offering to the subjects. The act of injection of the liquid into the mouth also minimised the yield stress effect and maximised the effects of viscosity alone.
3.8.2 Flavour

As studies have shown that intensity of taste can have significant temporal and physical effects on swallowing behaviour (Leow et al., 2007; Logemann et al., 1995; Pelletier and Dhanaraj, 2006), water was used as the mixing agent to minimise the effects of taste when comparing honey-thick liquid to water swallows in the pilot study. Unfortunately palatability decreased significantly as viscosity increased and several participants gagged on honey-thick consistency. As a result, it was decided to use a commercially available mildly sweetened, apple flavoured liquid (Mizone® Active Water, Crisp Apple, Frucor Beverages Limited, New Zealand) to undertake the viscosity experiments. This was universally acceptable to all participants with no participants describing the Mizone based liquids as unpleasant.

3.8.3 Temperature

Starch based thickeners once fully gelatinised follow the Arrhenius relationship in which increases in temperature cause starch suspensions to decrease in viscosity. However starch granules in suspension that have not fully gelatinised, swell further under heating resulting in an increase of viscosity as they reach their gelatinization temperature. As the viscosity ranges produced by the National Dysphagia Diet (US) were measured at 25°C and Starch based thickeners can become more viscous as they move either direction from 25°C (Garcia et al., 2008). All experimental liquids for oral administration were kept in a 20-litre glass water bath kept at 25°C. Temperature was checked by an in water digital thermometer (Aqua One, Southampton, United Kingdom) and maintained by a 25 Watt immersion element heater (Aqua One, Southampton, United Kingdom). To ensure temperature equalization, liquids were left overnight to equilibrate (see figure 10 A).
3.8.4 Time

Starch based thickeners are susceptible to alterations in viscosity with time (Dewar and Joyce, 2006). To allow consistency of viscosity, swallowing testing was carried out 3 minutes post mixing. Meticulous adherence to mixing instructions was followed and required the assistance of a research assistant to prepare and deliver all samples (see figure 3.10 B).

3.8.5 Viscosity

Samples of Thicken Up® with mixing instructions and measuring spoons were sent to Lidia Motoi (Food Innovation, Bioresources Engineering & Chemistry, Canterbury Agriculture & Science Centre Lincoln) for assessment of viscosity. Manufacturers instructions for honey-thick viscosity required the addition of 1 level tablespoon and 1 level teaspoon measure of Thicken Up® (This was calculated to equal 6.427 g) to 120 ml of Mizone®. Viscosity and Strain rate data can be seen in table 3.1 and figure 3.11. The viscosity results placed the honey-thick liquid comfortably within the USA fluid viscosity class boundaries.
Table 3.1: Viscosity and yield stress of test liquids at 25°C. Courtesy of Lidia Motoi (Food Innovation, Bioresources Engineering & Chemistry, Canterbury Agriculture & Science Centre Lincoln)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Shear rate (1/s)</th>
<th>Shear stress (τ)</th>
<th>Viscosity (cP)</th>
<th>Yield stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>50</td>
<td>0.04</td>
<td>8</td>
<td>0.0019</td>
</tr>
<tr>
<td>Mizone®</td>
<td>50</td>
<td>0.08</td>
<td>17</td>
<td>0.0016</td>
</tr>
<tr>
<td>Honey</td>
<td>50</td>
<td>26.18</td>
<td>523</td>
<td>0.1508</td>
</tr>
</tbody>
</table>

![Graph showing Viscosity versus Shear rate for different liquids at 25°C](image)

Figure 3.11: Viscosity across multiple strain rates at 25°C. Courtesy of Lidia Motoi (Food Innovation, Bioresources Engineering & Chemistry, Canterbury Agriculture & Science Centre Lincoln)
3.9 Testing protocols

All recordings were performed at the University of Otago, School of Dentistry in a quiet testing laboratory (see figure 3.12). Experimentation was carried out under aseptic conditions with the intra-oral testing appliance cold sterilised using a 70% ethanol solution before and after testing.

The pressure-recording appliance was immersed in clean tap water and then the palatal contact surface was evenly coated with an even dusting of a denture adhesive powder (Holdtite® Bouty S.p.A., Italy). Taking care not to touch the pressure transducers, the appliance was gently placed in the subject’s mouth with the instruction to suck the plate onto the roof of the mouth. The participant was asked if any air could pass under the plate or if the bite was altered in anyway. More adhesive was added if airflow was perceived and the plate was manually seated in areas of poor fit. The plate was then left in the mouth for a 15-minute equilibration period, during which, the submental EMG electrodes were attached.

During acclimatisation, the participants were able to interact freely to get accustomed to the denture plate. Prior to the testing sessions the participants were asked to look ahead at the far wall and assume a relaxed, natural, upright head position. This was undertaken to standardise results as alterations in head position have been shown to affect intra-oral pressures (Archer and Vig, 1985; Ingervall and Thuer, 1988).
Previous experimentation in this department utilising this methodology has demonstrated excellent intra-subject repeatability and recording reliability (Kieser et al., 2008; Kennedy et al., 2010). As such, 3 recording sessions were conducted. Each swallowing test was to be repeated at 6 times in order to reduce intra-individual variation and achieve more accurate means (Proffit et al., 1964). The first session was used solely to accommodate the subject to the experimental environment and minimise the effects of apprehension and novel environment on the swallow. The data recorded in the following 2 sessions were used for analysis.

3.9.1 Testing sequence

The first test involved the subject swallowing 10 ml boluses of water and flavoured liquids of varying consistency. To minimise delay and possible changes to the viscosity, each liquid was swallowed 6 times. The subject was asked to hold the liquid bolus in the mouth until the command to swallow was given. For every test involving introducing a bolus, the
participants were given the instructions to “deliver” the bolus, to “hold” the bolus until the sEMG trace settled and finally to “swallow” the bolus. This holding phase was for a maximum of 2 s prior to the instruction to swallow to minimise effects of saliva on consistency. The order of bolus testing was water, Mizone®, and then honey-thick Mizone®. The subjects had a water swallow between each change in consistency to clear the oral cavity. The water and Mizone® swallows were delivered via a standard 50 ml plastic measuring cup. The thickened liquids were delivered via a 20 ml syringe to minimise any effects of thixotropic liquid behaviour.

Duration between swallows was 20 s. This was to ensure that all swallowing behaviour was recorded, allowing sufficient time for any secondary clearance swallows to be recorded should they occur with changes in viscosity (Okada et al., 2007).

### 3.9.2 Controls

To reduce variation in experimental conditions, the same operator was responsible for preparing the liquids with the same batch of Thicken Up® throughout the entire experiment. Similarly, the same operator was responsible for monitoring the recordings and giving commands. To ensure accuracy with post processing, pre-set commands were entered into the recording data via short-cut keys during recording. These indicated the substance being trialled and the commands “deliver”, ” hold” and “swallow”. Each subject acted as his or her own control throughout the experiment for intra-individual and inter-session comparison. The tests were also carried out in the late afternoon to minimise any diurnal effects on swallowing behaviour.

### 3.10 Data analysis

Data were recorded during the experimentation by the LabChart® 7.0.2 software. These were saved as named and dated session files onto the hard-drive of the recording computer. Each run of swallows in each liquid were then cut and appended to a separate file, labelled and saved. Each individual swallow was then selected as a 12 s block, saved and then
appended to a file for each individual. This resulted in 10 individual files of 36 swallows consisting of 3 liquids with 12 swallows each.

### 3.10.1 Initiation of swallowing

Previous researchers from this facility have utilised the initial drop in pressure of the anterior midline channel as a marker for initiation of swallowing (Kieser et al., 2008; Kennedy et al., 2010). However with increasing viscosity and during the hold and swallow commands this phenomenon was obscured. As a result submental sEMG was utilised to allow an accurate onset of swallowing function. The use of this methodology to identify swallowing signals was validated in research by Crary et al. (2007) and Taniguchi et al. (2008).

In order to analyse the submental sEMG signal, it was low pass filtered at 20Hz to remove interference then high pass filtered at 10Hz to remove baseline movement drift. The signal was then rectified as detailed previously. This filtered and rectified channel was then maximised and time axis expanded to 1:10 on LabChart® to facilitate selection of the initiation marker (see figure 3.13 A).

Much non-swallowing activity was observed during the loading and hold phase of the swallow as well as after the swallow. This was likely due to the fact that it only takes 1 activated muscle in the submental complex to trigger a change in sEMG output (Ding et al., 2002). Therefore, to locate the point of initiation of swallowing, an arbitrary level above the mV baseline was individually chosen for each participant. This was checked so that it coincided with a change in the anterior midline channel pressure change from baseline. See figure (3.13 B).
Figure 3.13: A) Filtering and rectification of raw sEMG signal; B) Selection of initiation of swallowing at 5mV threshold.

3.10.2 Termination

Despite filtering and rectification of the sEMG signal, it was not possible to reliably locate an offset from which to classify the end of the swallow sequence. This was primarily due to background interference and as such the offset of swallowing duration was chosen on the last major, positive, inflection of the posterior midline channel pressure fall. This was located with the posterior midline channel maximised and set to 1:10 time axis (see figure 3.14).
3.10.3 Pressure overlay point

Several locations were assessed to overlay pressure profiles in the pilot study. Submental sEMG proved to have insufficient correlation to pressure patterns to allow overlaying both within and between participants. The peak pressure of the last major rise of the mid-palatal channel was also trialled; however, use of this point resulted in a shift of the overlay patterns to the end stages of the swallowing pattern and hence initial stages were lost in the overlay. Consequently, this was changed to the initial pressure peak of the mid-palatal channel. This point provided a consistent pattern of behaviours within and between individuals, allowing for analysis of the initial, mid and final stages of the swallow. The peak of the mid-palatal channel initial major pressure rise was objectively located using the software’s peak-detection function. This was subsequently marked onto the data file. After marking with peak initial mid-palatal pressure rise, submental sEMG initiation and posterior midline terminal pressure inflexion termination, each individual swallow was selected and saved as a block of time. This was achieved by selecting 3 s before, and 5 s
after the sEMG initiation marker. These files were subsequently re-appended as a shorter file of 12 swallows for each bolus analysis. This enabled each individual swallow to be overlaid for analysis using the Scope and Zoom function of the LabChart® 7.0.2 software (see figure 3.15).

Figure 3.15: Sequential swallows appended as 8 s blocks and labelled with sEMG initiation, initial midpalatal peak and termination.

The Scope® function allowed the simultaneous overlaying of multiple pressure profiles on a fixed point within the swallow (see figure 3.16). As discussed previously, this was chosen as the peak of the initial mid-palatal major pressure rise. It was then possible to create an overall average graph for each participant for subsequent analysis of timing and polarity of absolute pressure patterns.
Figure 3.16: Scope® overlay of 12 midline channel swallows on the initial midpalatal peak. Black line = average swallow, Blue lines = 12 overlaid swallows. Subject JF shown on the left and JP on the right.

All 7 channels were selected and opened using the Zoom® function of the LabChart® 7.0.2 software. This placed the selected channels on the same pressure and time axes for simultaneous analysis. The channels were initially represented graphically with all 7 channels to garner an over impression of pressure behaviour. For ease of analysis and descriptive purposes, they were subsequently divided into the midline and lateral channels (see figure 3.17).
Figure 3.17: Multi-channel Zoom® of Scope® average swallows

Following descriptive analysis of each individual’s pressure profile absolute pressure data was extracted from each individual swallow using the Datapad function (see figure 3.18 A). This was in the form of maxima, minima as well as the mean and root mean squared from initiation to termination of each swallowing event. These data were then exported to Microsoft Excel to enable calculation of individual means and standard deviation (see figure 3.18 B). These were subsequently graphically represented and statistically analysed.
Figure 3.18 A) Screen-shot of Datapad for Mean of water swallows; B) Screen-shot of data transfer to Microsoft Excel Spreadsheet.
It was not possible to use the Scope® function with individual average pressure profiles. Therefore, to create the generic overlay of all 10 participants a single pressure profile that best fit the average graph from each individual was selected (see figure 3.19).

Figure 3.19: Example of swallow from midline channels (coloured red, brown, grey) that best fits the average swallow in black (in this case it was the 12th swallow).

These 10 single swallow files were then appended to a best-fit file and overlaid on the initial mid-palatal peak to allow the creation of the generic average swallow with the Scope® function (see figure 3.20). This swallow pattern was used to define the average swallow pattern and base the development of pressure profile stages universal to all participants.
Figure 3.20: A) Overlay of best-fit swallows from 10 participants. (blue lines = individual profiles, black line = average profile); B) Resultant composite generic average graph scaled for analysis

The best-fit data did not accurately represent the true average of each individual’s minima, maxima, mean, and root mean square (RMS). As opposed to the mean, which averages positive and negative pressures throughout the swallow, RMS was used as a measure to calculate total work done on the bolus during the swallow as it factors both positive and negative pressure during throughout the swallow duration. To allow description of sample means, the average of each individual’s 12 swallows was taken for each bolus and subsequently averaged using Microsoft Excel. This was also subsequently statistically analysed and graphically represented.

3.10.4 Statistics

This was essentially a descriptive study based on the analysis of waveforms. However for the statistical analysis of durational and absolute pressure measurements it was assumed that pairs of data were matched. This was due to the fact that within individuals, conditions were matched with respect to time of day, swallow volume, experimental timing, recording and calibration protocol. Within each of the experiments the only significant variables were taste, in the case of water versus Crisp Apple flavoured Mizone® (assuming that
viscosity was of negligible difference) and viscosity, in the case of the Mizone® versus honey-thick Mizone®. Similarly when comparing generic averages all conditions were matched within and between the individuals. Therefore, a paired, 2-tailed t-test was utilised to analyse significance of variation. The level of statistical significance, indicating that the probability of any differences observed not being due to chance, was set at p<0.05. As this was not an in-vitro experiment, variability within pressure and timing measures were biological in nature. It was decided to use standard deviation on the pressure and duration graphs.
4 Results

The intra-oral pressure data were recorded from each subject over 2 consecutive days. Each subject was asked to perform 6, consecutive, discrete swallows of 10 ml volume for each liquid type. These were of water, Mizone® and Mizone® thickened to a honey-thick consistency. Pressure data were recorded from each of 7 transducers. These were numbered 1 to 7. Anterior, mid-palate and posterior palate (channels 1, 2 and 3) right anterior and right posterior (channels 4 and 5) and left anterior and posterior (channels 6 and 7). The pressure data recorded at 1 kHz were analysed by the LabChart® 7.2.1 and Scope® software by ADInstruments. An average pressure profile was created from the 12 discrete swallows for each liquid. Various channels were then overlaid on the same pressure (kPa) and time (s) axes. This enabled a simultaneous sequential description of onset, peak and duration of pressures at different regions of the hard palate. As previous researchers at this facility have only analysed the midline sites, this research will expand on midline understanding and for the first time describe the behaviour of the lateral absolute intra-oral pressures.

Raw pressure data from the LabChart® software was exported to Microsoft Excel™ for further analysis and graphical representation. The duration of swallowing from submental sEMG onset to the termination at the posterior mid palatal channel was derived for each swallow. Comparative statistics were then applied to the maximum, minimum, mean and root mean square (RMS) of pressures generated at each channel during the swallow. Comparison was made between water and Mizone® with the only variable being taste and then Mizone® versus honey-thickened Mizone® with the only variable being consistency. 2-tailed paired student’s t-tests were used to assess statistical difference between these comparisons.

Utilising the Scope® software a generic or composite swallow based on the swallow profile from each of the 10 subjects could be created. This was achieved by appending each individual’s best-fit swallow profile then overlaying them on the mid-palatal initial pressure peak. This could be described and analysed in a manner similar to the individual analysis.
4.1 Individual results

4.1.1 BA results

Participant BA displays a monophasic, mainly positive swallowing pressure pattern, with an absolute pressure range of 80 kPa from -10 to 70 kPa (see figure 4.1).

**Water swallowing sequence**

Sequentially, the anterior channel rises first with anterior lateral peak pressure occurring midway between the anterior and mid palatal midline peaks. The posterior lateral onset occurs at the same time as the anterior and maintains a plateau of high pressure throughout the swallow. An initial anterior peak is then followed by a subsequent smaller peak that coincides with the mid and posterior peaks. The mid and posterior peaks occur in close temporal proximity from anterior to posterior with the secondary anterior peak occurring between these. The anterior lateral pattern has a double peak similar to that of the anterior channel. The posterior lateral channels have a plateau of pressure with a less defined double peak. All fall away steadily after the swallow is completed. There is a marked right anterior and right posterior pressure differential with the water swallow.

**Mizone® swallows**

Along the midline there is very little difference sequentially between the water and Mizone® swallows. The same lateral sequential pattern is also evident in the Mizone swallows with a slight delay in the onset of the anterior lateral pressure wave. The right anterior and posterior pressure differential is less marked.

**Honey swallows**

With the honey swallows all 3 midline channels display a secondary pressure wave that runs from anterior to posterior. This is comprised of a large fall in pressure followed by a secondary pressure wave. In the honey swallows, there is a markedly different pressure pattern with a loss of the initial anterior pressure peak. There is, instead, a slight drop in pressure that occurs with a mid and posterior small pressure rise. There is then a large pressure rise with anterior onset followed by mid then posterior channels.
<table>
<thead>
<tr>
<th>Channels</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 7 Channels</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>70 kPa</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>25 kPa</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
<tr>
<td>-10 kPa</td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
<tr>
<td>Midline Channels</td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
<tr>
<td>60 kPa</td>
<td><img src="image16" alt="Graph" /></td>
<td><img src="image17" alt="Graph" /></td>
<td><img src="image18" alt="Graph" /></td>
</tr>
<tr>
<td>30 kPa</td>
<td><img src="image19" alt="Graph" /></td>
<td><img src="image20" alt="Graph" /></td>
<td><img src="image21" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image22" alt="Graph" /></td>
<td><img src="image23" alt="Graph" /></td>
<td><img src="image24" alt="Graph" /></td>
</tr>
<tr>
<td>Lateral Channels</td>
<td><img src="image25" alt="Graph" /></td>
<td><img src="image26" alt="Graph" /></td>
<td><img src="image27" alt="Graph" /></td>
</tr>
<tr>
<td>70 kPa</td>
<td><img src="image28" alt="Graph" /></td>
<td><img src="image29" alt="Graph" /></td>
<td><img src="image30" alt="Graph" /></td>
</tr>
<tr>
<td>25 kPa</td>
<td><img src="image31" alt="Graph" /></td>
<td><img src="image32" alt="Graph" /></td>
<td><img src="image33" alt="Graph" /></td>
</tr>
<tr>
<td>-10 kPa</td>
<td><img src="image34" alt="Graph" /></td>
<td><img src="image35" alt="Graph" /></td>
<td><img src="image36" alt="Graph" /></td>
</tr>
<tr>
<td>1 second =</td>
<td><img src="image37" alt="Graph" /></td>
<td><img src="image38" alt="Graph" /></td>
<td><img src="image39" alt="Graph" /></td>
</tr>
</tbody>
</table>

Figure 4.1: Averaged pressure profiles for BA.
Laterality and onset

Over all the swallows, BA displays a right-sided dominance in the posterior lateral channels. In the water swallows there was a left sided anterior dominance however there was large variation in swallows pressures in this channel. Overall, there was relative equivalence in the anterior channels. The onset of BA’s initial anterior pressure rise precedes that of the mid and posterior in all liquids (see table 4.1).

Table 4.1: Midline primary pressure wave sequence for BA.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Onset (s)</td>
<td>Peak (s)</td>
<td>Onset (s)</td>
</tr>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0.228</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.45</td>
<td>0.65</td>
<td>0.409</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.46</td>
<td>0.667</td>
<td>0.464</td>
</tr>
</tbody>
</table>

BA displays a rapid (0.058 s to 0.096 s) peristaltic wave where the mid palatal peak precedes the anterior peak in all liquids. The posterior peak is the terminal event in all swallows (see table 4.2).

Table 4.2: Relative timing of primary midline peak pressures for BA.

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water (s)</th>
<th>Mizone®(s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.007</td>
<td>0.023</td>
<td>0.064</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>-0.051</td>
<td>-0.047</td>
<td>-0.032</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.058</td>
<td>0.070</td>
<td>0.096</td>
</tr>
</tbody>
</table>

Absolute pressure analysis

The following pressure data are based on the average of 12 swallows for each liquid. Paired 2-tailed t-tests were performed to assess if a statistically significant variation was noted between water and Mizone® and then, Mizone® and honey-thick Mizone®.
Participant BA showed significant differences with a tendency to lower swallowing pressures across most channels with Mizone® (see table 4.3). The size of this reduction was in the vicinity of 5 kPa (see figure 4.2). This tendency was not noted in the posterior midline channel.
**Figure 4.3:** Mizone® versus honey pressure analysis for BA.

**Table 4.4:** Statistical significance between Mizone® and honey swallowing pressures for BA.

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.105</td>
<td>0.124</td>
<td>0.010</td>
<td>0.001</td>
<td>0.001</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.001</td>
<td>0.001</td>
<td>0.689</td>
<td>0.111</td>
<td>0.001</td>
<td>0.917</td>
<td>0.063</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>0.538</td>
<td>0.009</td>
<td>0.006</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
</tr>
</tbody>
</table>

BA showed significant changes in the mid palatal posterior channel with significant increases in mean maximum and RMS (see table 4.4). The mean pressure increases in all lateral and the posterior midpalatal channels (see figure 4.3). BA also had a significant reduction in minimum pressure in the anterior and mid palatal regions due to the marked pressure drop that precedes the secondary pressure wave.
Swallowing duration

There was no difference in duration between water and Mizone®. There was a significant difference between Mizone® and Honey with the duration more than doubling (see figure 4.4).

\[ p = 0.598 \quad p < 0.001 \]

Figure 4.4: Average swallowing durations for BA.
4.1.2 BE results

BE has biphasic swallows with a pressure range in the region of 90 kPa lying between -15 to 75 kPa with the largest range in the lateral channels (see figure 5).

Water swallowing sequence

The right anterior and posterior lateral pressures rise prior to initial mid palatal rise with the left anterior lateral pressure rise coincident with the mid palatal pressure rise. All 7 channels rise sharply then fall in a tight uniform pattern. Prior to the secondary pressure wave in the mid and posterior channels, an anterior pressure rise occurs concurrently with a transient pressure drop in the mid-palatal and midline posterior channels. This is followed by a sequential anterior to posterior secondary pressure wave with a tight temporal relationship between all channels.

Mizone® swallowing sequence

The sequential pressure pattern evident in the water swallows is conserved in the Mizone® swallows with an initial low pressure wave followed by a second pressure wave of greater amplitude. The pressure range between the right anterior and left posterior channels is reduced. The secondary pressure wave follows the same pattern as the water swallows.

Honey swallow sequence

The sequence of pressure onset shows a fall in pressure at the anterior right and anterior midline channels as the left anterior, midpalatal and posterior midline channels begin to elevate. After an early peak, the left anterior, mid-palatal and right and midline posterior channels then dip slightly as the anterior midline rises to a peak. This is followed by a sequential pressure wave along the midline. The right anterior lateral channel follows the same pattern as the anterior midline with a slight delay. The right posterior channel maintains high pressure with minor changes closely aligned to the midpalatal channel. After peaking all channels fall away with the right anterior being the last to do so.
## Figure 4.5: Averaged pressure profiles for BE.
**Laterality and onset**

BE shows similar lateral pressures anteriorly, however there is a marked right-sided pressure pattern in the posterior region. BE produced a tight temporal alignment with the primary pressure wave. The posterior peak occurs before the middle in all cases and before the anterior in water and honey (see table 4.5). The time range the primary peaks occur in is approximately 0.04 s (see table 4.6).

**Table 4.5: Midline primary pressure wave sequence for BE.**

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>Onset (s)</td>
<td>Peak (s)</td>
<td>Onset (s)</td>
</tr>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0.233</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.01</td>
<td>0.243</td>
<td>0.066</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.098</td>
<td>0.205</td>
<td>0.052</td>
</tr>
</tbody>
</table>

**Table 4.6: Relative timing of primary midline peak pressures for BE.**

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water (s)</th>
<th>Mizone (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>-0.032</td>
<td>0.009</td>
<td>-0.007</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.009</td>
<td>0.033</td>
<td>0.03</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>-0.041</td>
<td>-0.024</td>
<td>-0.037</td>
</tr>
</tbody>
</table>
Figure 4.6: Water versus Mizone® pressure analysis for BE.

Table 4.7: Statistical significance between water and Mizone® swallowing pressures for BE.

<table>
<thead>
<tr>
<th>Water Vs Mizone® p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.244</td>
<td>0.001</td>
<td>0.008</td>
<td>0.013</td>
</tr>
<tr>
<td>Max</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.674</td>
<td>0.001</td>
<td>0.011</td>
<td>0.205</td>
</tr>
<tr>
<td>Min</td>
<td>0.023</td>
<td>0.001</td>
<td>0.001</td>
<td>0.304</td>
<td>0.001</td>
<td>0.009</td>
<td>0.015</td>
</tr>
<tr>
<td>RMS</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.252</td>
<td>0.001</td>
<td>0.008</td>
<td>0.014</td>
</tr>
</tbody>
</table>

BE had a significant pressure drop from water to Mizone in all midline channels (see table 4.7). The right anterior channel, the only channel to display sub-atmospheric pressure, rises with Mizone® (see figure 4.6).
Figure 4.7: Mizone® versus honey pressure analysis for BE.

Table 4.8: Statistical significance between Mizone® and honey swallowing pressures for BE.

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.015</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.291</td>
<td>0.140</td>
</tr>
<tr>
<td>Max</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.034</td>
<td>0.002</td>
</tr>
<tr>
<td>Min</td>
<td>0.001</td>
<td>0.002</td>
<td>0.128</td>
<td>0.170</td>
<td>0.446</td>
<td>0.920</td>
<td>0.001</td>
</tr>
<tr>
<td>RMS</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.277</td>
<td>0.550</td>
</tr>
</tbody>
</table>

BE showed a clinically significant increase in mean, max and RMS in all midline and anterior lateral channels with an increase in the maximum in all 7 channels (see table 4.8). Overall, honey consistency increased intra-oral pressure with a significant fall in pressure at the anterior midline and left posterior (see figure 4.7).
**Swallowing duration**

![Swallowing duration graph](image)

\[ p = 0.706 \quad p < 0.001 \]

**Figure 4.8:** Average swallowing durations for BE.

There was no significant difference in the duration of the water versus Mizone swallows. BE displayed a significantly longer swallowing duration with honey consistency more than doubling the time to swallow (see figure 4.8).
4.1.3 CL results

CL shows a biphasic swallowing pattern with a marked primary swallow followed by a subtle secondary swallow. The pressure range is in the region of 75 kPa between -25 to 50 kPa (see figure 4.9).

Water swallowing sequence
Swallowing onset begins with a sharp pressure rise and fall at the anterior midline. After this initial peak, the lateral sensors begin to increase in pressure steadily maintaining a peak throughout which the midline sensor sequential midline wave occurs from anterior to posterior. A secondary lateral pressure peak occurs as the midline channels fall away. A secondary, smaller, midline pressure wave begins as the lateral channels all fall away. This secondary wave has a well-defined sequential onset and peak from anterior to posterior.

Mizone® sequence
The Mizone® swallow differs mainly in the fact that the initial midline pressure is maintained and doesn’t fall away as in the water swallows. The remainder of the swallow is very similar with respect to onsets and peak timings.

Honey sequence
There is an earlier rise in the anterior midline channel that maintains a plateau before the onset of the lateral channels. This is followed by the sequential, midline, anterior to posterior pressure wave. There is very little difference overall in sequence and pattern of the honey swallows.
## All 7 Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 kPa</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>-25 kPa</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = .................................................................

anterior  mid-palate  posterior  right anterior  right posterior  left anterior  left posterior

## Midline Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kPa</td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
<tr>
<td>-10 kPa</td>
<td><img src="image16" alt="Graph" /></td>
<td><img src="image17" alt="Graph" /></td>
<td><img src="image18" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = .................................................................

anterior  mid-palate  posterior

## Lateral Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 kPa</td>
<td><img src="image19" alt="Graph" /></td>
<td><img src="image20" alt="Graph" /></td>
<td><img src="image21" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image22" alt="Graph" /></td>
<td><img src="image23" alt="Graph" /></td>
<td><img src="image24" alt="Graph" /></td>
</tr>
<tr>
<td>-25 kPa</td>
<td><img src="image25" alt="Graph" /></td>
<td><img src="image26" alt="Graph" /></td>
<td><img src="image27" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = .................................................................

right anterior  right posterior  left anterior  left posterior

**Figure 4.9:** Averaged pressure profiles for CL.
**Laterality and onset**

The pressures of this swallow pattern show a marked asymmetry between anterior and posterior lateral pressures. The right anterior mean pressure is 41 kPa with the left anterior markedly lower at 1.6 kPa the midline pressure is inbetween at 13.6 kPa. This shows a marked right-sided anterior palatal pressure. The posterior pressure is the total reverse with a distinct, left-sided pressure bias. In all liquids, CL has a very similar sequence of pressure onset with a well-defined sequential anterior to posterior terminal pressure wave (see table 4.9). There duration of the peak pressure wave was 0.11 to 0.15 s (see table 4.10).

**Table 4.9: Midline primary pressure wave sequence for CL.**

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>Onset (s)</td>
<td>0</td>
<td>0.498</td>
</tr>
<tr>
<td></td>
<td>Peak (s)</td>
<td>0.53</td>
<td>0.561</td>
</tr>
<tr>
<td>Middle</td>
<td>Onset (s)</td>
<td>0.496</td>
<td>0.505</td>
</tr>
<tr>
<td></td>
<td>Peak (s)</td>
<td>0.588</td>
<td>0.551</td>
</tr>
<tr>
<td>Posterior</td>
<td>Onset (s)</td>
<td>0.589</td>
<td>0.550</td>
</tr>
<tr>
<td></td>
<td>Peak (s)</td>
<td>0.654</td>
<td>0.621</td>
</tr>
</tbody>
</table>

**Table 4.10: Relative timing of primary midline peak pressures for CL.**

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water (s)</th>
<th>Mizone® (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.116</td>
<td>0.121</td>
<td>0.151</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.047</td>
<td>0.050</td>
<td>0.070</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.069</td>
<td>0.069</td>
<td>0.081</td>
</tr>
</tbody>
</table>
Figure 4.10: Water versus Mizone® pressure analysis for CL.

Table 4.11: Statistical significance between water and Mizone® swallow pressures for CL.

<table>
<thead>
<tr>
<th>Water Vs Mizone® p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.007</td>
<td>0.621</td>
<td>0.180</td>
<td>0.457</td>
<td>0.299</td>
<td>0.314</td>
<td>0.087</td>
</tr>
<tr>
<td>Max</td>
<td>0.165</td>
<td>0.012</td>
<td>0.107</td>
<td>0.186</td>
<td>0.024</td>
<td>0.054</td>
<td>0.011</td>
</tr>
<tr>
<td>Min</td>
<td>0.004</td>
<td>0.068</td>
<td>0.081</td>
<td>0.292</td>
<td>0.055</td>
<td>0.002</td>
<td>0.810</td>
</tr>
<tr>
<td>RMS</td>
<td>0.034</td>
<td>0.552</td>
<td>0.107</td>
<td>0.349</td>
<td>0.088</td>
<td>0.047</td>
<td>0.052</td>
</tr>
</tbody>
</table>

CL showed a significant fall in anterior mean min and RMS at the anterior channel (see table 4.11). There was large variation between individual swallows in the midline channels with less observed in the lateral channels. The mid-palatal channel showed a significant increase in maximum pressure in the region of 5 kPa (see figure 4.10).
Figure 4.11: Mizone® versus honey pressure analysis for CL.

Table 4.12: Statistical significance between Mizone® and honey swallowing pressures for CL.

<table>
<thead>
<tr>
<th>Mizone® Vs. Honey p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.070</td>
<td>0.755</td>
<td>0.618</td>
<td>0.045</td>
<td>0.044</td>
<td>0.167</td>
<td>0.017</td>
</tr>
<tr>
<td>Max</td>
<td>0.123</td>
<td>0.186</td>
<td>0.150</td>
<td>0.535</td>
<td>0.660</td>
<td>0.861</td>
<td>0.231</td>
</tr>
<tr>
<td>Min</td>
<td>0.862</td>
<td>0.380</td>
<td>0.014</td>
<td>0.524</td>
<td>0.313</td>
<td>0.205</td>
<td>0.670</td>
</tr>
<tr>
<td>RMS</td>
<td>0.033</td>
<td>0.001</td>
<td>0.016</td>
<td>0.052</td>
<td>0.043</td>
<td>0.560</td>
<td>0.022</td>
</tr>
</tbody>
</table>

CL showed a small, yet significant, fall in RMS across the midline channels and the left posterior lateral channel this was in the region of 3 kPa (see figure 4.11 and table 4.12). There was no significant difference in the mean maximum pressure across any channels. The mean pressure fell slightly in both anterior lateral and the left posterior lateral channels.
Swallowing duration

There was no significant difference in duration of water and Mizone® swallows. CL showed a significant increase in duration for the honey consistency (see figure 4.12).
4.1.4 CM Results

CM has a marked biphasic swallow and high swallowing pressures in the range of 0 to 80 kPa (see figure 4.13).

**Water swallowing sequence**
Initial onset begins at the lateral channels, closely followed by the anterior palate with a sequential onset of mid then posterior midline channels. Initial peaks occur firstly at the posterior lateral, then anterior lateral, then nearly simultaneously at the anterior midline and mid palatal channels. The last sensor to record a pressure peak is the posterior midline. Following the initial pressure wave there is a secondary pressure wave with a significant fall in pressure at the mid and posterior midline as the lateral and anterior palatal pressure peaks. This is followed by a well-defined sequential onset of pressure from mid to posterior midline. The pressures of the anterior and lateral palate are significantly higher than the mid and posterior palate with a peak pressure difference between the anterior palate and the posterior palate in the region of 50 kPa.

**Mizone swallows**
CM’s Mizone swallows follow a very similar pattern to the water swallows. There is a slightly earlier onset and peak of the anterior midline channel. Again there is a marked uniformity of lateral pressure rise and peak that precedes the mid and posterior peaks in both pressure waves of the swallows. Again the anterior and lateral pressure are significantly higher than the mid and posterior midline pressure waves

**Honey swallows**
These also follow a very similar pattern of onset and sequence.
Figure 4.13: Averaged pressure profiles for CM.
**Laterality and onset**

CM shows a posterior right-sided dominance with relatively equal anterior channels. CM shows a sequential onset of anterior to posterior pressure waves with a tight temporal relationship between the anterior and middle channels with the posterior channel peaking last (see table 4.13). The duration between peak pressures was 0.022 to 0.049 (see table 4.14).

### Table 4.13: Midline primary pressure wave sequence for CM.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Onset (s)</td>
<td>Peak (s)</td>
<td>Onset (s)</td>
</tr>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0.395</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.22</td>
<td>0.390</td>
<td>0.225</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.284</td>
<td>0.418</td>
<td>0.280</td>
</tr>
</tbody>
</table>

### Table 4.14: Relative timing of primary midline peak pressures for CM.

<table>
<thead>
<tr>
<th></th>
<th>Water (s)</th>
<th>Mizone (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.024</td>
<td>0.049</td>
<td>0.022</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>-0.005</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.029</td>
<td>0.039</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Figure 4.14: Water versus Mizone® pressure analysis for CM.

Table 4.15: Statistical significance between water and Mizone® swallowing pressures for CM.

<table>
<thead>
<tr>
<th>Water Vs Mizone® p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.318</td>
<td>0.451</td>
<td>0.158</td>
<td>0.093</td>
<td>0.151</td>
<td>0.912</td>
<td>0.865</td>
</tr>
<tr>
<td>Max</td>
<td>0.833</td>
<td>0.587</td>
<td>0.784</td>
<td>0.457</td>
<td>0.714</td>
<td>0.723</td>
<td>0.433</td>
</tr>
<tr>
<td>Min</td>
<td>0.183</td>
<td>0.610</td>
<td>0.910</td>
<td>0.001</td>
<td>0.033</td>
<td>0.999</td>
<td>0.391</td>
</tr>
<tr>
<td>RMS</td>
<td>0.426</td>
<td>0.433</td>
<td>0.0496</td>
<td>0.130</td>
<td>0.231</td>
<td>0.932</td>
<td>0.872</td>
</tr>
</tbody>
</table>

The only statistically significant differences are an increase in pressure at the right and left anterior lateral channels and a slight reduction in posterior RMS on Mizone® (see figure 4.14 and table 4.15).
Figure 4.15: Mizone® versus honey pressure analysis for CM.

Table 4.16: Statistical significance between Mizone® and honey swallowing pressures for CM.

<table>
<thead>
<tr>
<th>Mizone® Vs. Honey p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.123</td>
<td>0.411</td>
<td><strong>0.006</strong></td>
<td>0.713</td>
<td>0.706</td>
<td>0.061</td>
<td><strong>0.045</strong></td>
</tr>
<tr>
<td>Max</td>
<td>0.150</td>
<td>0.722</td>
<td>0.288</td>
<td>0.857</td>
<td>0.558</td>
<td>0.115</td>
<td>0.894</td>
</tr>
<tr>
<td>Min</td>
<td>0.171</td>
<td>0.552</td>
<td>0.369</td>
<td>0.309</td>
<td>0.822</td>
<td>0.132</td>
<td><strong>0.003</strong></td>
</tr>
<tr>
<td>RMS</td>
<td>0.233</td>
<td>0.464</td>
<td><strong>0.005</strong></td>
<td>0.790</td>
<td>0.651</td>
<td>0.056</td>
<td>0.069</td>
</tr>
</tbody>
</table>

There was a significant increase in mean pressure at the posterior and left posterior channels (see table 4.16). Minimum pressure was increased at the left posterior and RMS was increased at the posterior midline channel. Overall there was very little change between the liquids (see figure 4.15).
Swallowing duration
There was no significant difference between water and Mizone® or Mizone and honey (see figure 4.16).
4.1.5 DK results

DK has a complex swallow that consists of a predominantly sub atmospheric pressure anteriorly rising to a high pressure in the posterior midline. DK displays a monophasic pattern with an initial major pressure wave. The pressure range is in the region of 65 kPa from -20 to 45 kPa (see figure 4.17).

Water swallowing sequence

On initiation the pressure rises at the mid and posterior midline as the anterior palatal pressure falls. This is then followed by a sequential anterior to posterior midline positive pressure wave. A simultaneous lateral palatal pressure rise occurs on all 4 channels prior to the midline pressure wave and holds during this event then falls away with the passing of the initial pressure wave.

Mizone swallows

The Mizone® swallows essentially follow the same sequential pattern as those of the water swallows, except there is an earlier more defined onset of the posterior midline channel pressure rise as the anterior midline channel is falling.

Honey swallows

The terminal pressure wave occurs in a more defined pressure rise in all 7 channels with the greatest difference being that of the lateral channels. These all display a markedly more defined simultaneous pressure rise that occurs prior to the midline pressure wave.
Figure 4.17: Averaged pressure profiles for DK.
**Laterality and onset**

DK has a reasonably symmetric pressure profile anteriorly with a pressure differential in the region of 5 kPa. There is a marked right-sided preference in the posterior region with a difference in the vicinity of 20 kPa. DK has a defined anterior to posterior onset sequence in all liquids with a defined anterior to posterior pressure wave (see table 4.17). There was a sequential pattern to the midline pressure peaks that lasted between 0.121 to 0.218 s (see table 4.18).

**Table 4.17: Midline primary pressure wave sequence for DK.**

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Onset (s)</td>
<td>Peak (s)</td>
<td>Onset (s)</td>
</tr>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0.406</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.328</td>
<td>0.601</td>
<td>0.049</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.449</td>
<td>0.66</td>
<td>0.457</td>
</tr>
</tbody>
</table>

**Table 4.18: Relative timing of primary midline peak pressures for DK.**

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water (s)</th>
<th>Mizone (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.218</td>
<td>0.121</td>
<td>0.201</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.155</td>
<td>0.050</td>
<td>0.108</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.063</td>
<td>0.069</td>
<td>0.093</td>
</tr>
</tbody>
</table>
The mid palatal channel had a minor increase in mean pressure and RMS. Both posterior channels showed an increase in pressure across all 4 parameters though in the region of 2 to 3 kPa. The right anterior channel showed a small difference in maximum pressure with a 2 kPa decrease (see figure 4.18 and table 4.19).
Figure 4.19: Mizone® versus honey pressure analysis for DK.

Table 4.20: Statistical significance between Mizone® and honey swallowing pressures for DK.

Mizone® Vs. Honey p values

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.680</td>
<td>0.066</td>
<td>0.013</td>
<td>0.002</td>
<td>0.575</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Max</td>
<td>0.098</td>
<td>0.004</td>
<td>0.151</td>
<td>0.200</td>
<td>0.011</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>Min</td>
<td>0.190</td>
<td>0.308</td>
<td>0.029</td>
<td>0.020</td>
<td>0.233</td>
<td>0.016</td>
<td>0.001</td>
</tr>
<tr>
<td>RMS</td>
<td>0.985</td>
<td>0.124</td>
<td>0.006</td>
<td>0.001</td>
<td>0.273</td>
<td>0.001</td>
<td>0.764</td>
</tr>
</tbody>
</table>

The posterior mid channel showed the largest clinical difference with significant increases in mean min and RMS with the honey swallows (see table 4.20). The minimum pressure in particular was increased by approximately 15 kPa. The middle channel showed a small increase in maximum pressure of approximately 2 kPa. In the honey swallows the right
anterior and both posterior lateral channels showed small statistical differences in the region of 3-5 kPa (see figure 4.19).

**Swallowing duration**

There was no significant difference in any of the swallows regarding duration (see figure 4.20).

\[ p = 0.145 \]

\[ p = 0.826 \]

**Figure 4.20:** Average swallowing durations for DK.
4.1.6 GD results

GD has monophasic swallowing with a subtle double movement in the posterior palate. There is a pressure range from 65 kPa (-10 kPa to 55 kPa) in water swallows to 95 kPa from -45 to 50 kPa in honey-thick swallows (see figure 4.21).

**Water swallowing sequence**

The anterior lateral palatal pressure rises followed soon by the anterior midline. The posterior lateral channels then rise before the mid-palatal pressure rise. The anterior lateral and midline pressures maintain a plateau until the mid-palatal midline peak and then fall way along with the posterior lateral channels. The final pressure wave is the posterior midline channel which has an intermediate phase followed by a small pressure rise.

**Mizone® swallowing sequence**

The Mizone swallowing follows the same sequence with a similar posterior midline double pressure pump.

**Honey swallowing sequence**

The honey swallowing displays an initial pressure wave similar to the others. However, a distinct negative pressure intermediate phase develops in the midline sensors. The initial pressure wave begins at the right anterior and mid anterior, followed by the left anterior with the pressure peaks of these occurring in a tight temporal relationship. The right and left posterior lateral channels peak next, followed in sequence by the mid, then posterior, palatal midline channels. Next, there is an intermediate anterior to posterior pressure drop followed by a lower pressure secondary sequential midline pressure wave. The size of the pressure gradient between maximum and minimum pressures in the intermediate region increases posteriorly. The pressure range of the left posterior displays significant variation, in the region of 50 kPa.
All 7 Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 kPa</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>10 kPa</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>-40 kPa</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ..................

anterior mid-palate posterior right anterior right posterior left anterior left posterior

Midline Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kPa</td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
<tr>
<td>-45 kPa</td>
<td><img src="image16" alt="Graph" /></td>
<td><img src="image17" alt="Graph" /></td>
<td><img src="image18" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ..................

anterior mid-palate posterior

Lateral Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 kPa</td>
<td><img src="image19" alt="Graph" /></td>
<td><img src="image20" alt="Graph" /></td>
<td><img src="image21" alt="Graph" /></td>
</tr>
<tr>
<td>25 kPa</td>
<td><img src="image22" alt="Graph" /></td>
<td><img src="image23" alt="Graph" /></td>
<td><img src="image24" alt="Graph" /></td>
</tr>
<tr>
<td>-10 kPa</td>
<td><img src="image25" alt="Graph" /></td>
<td><img src="image26" alt="Graph" /></td>
<td><img src="image27" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ..................

right anterior right posterior left anterior left posterior

Figure 4.21: Averaged pressure profiles for GD.
**Laterality and onset**

GD Displays a marked asymmetry in lateral pressure with anterior lateral channels showing a distinct right-sided preference with pressures approximately 40 kPa higher on this side. In the posterior the opposite pattern occurs with the left posterior showing a marked increase in pressure in the region of 25 kPa. GD displays a distinct sequential onset from anterior to posterior in the range of 0.3 s (see table 4.21). Pressure peaks occur in a similar manner with a clearly defined anterior to posterior pattern in all liquids lasting from 0.098 to 0.208s (see table 4.22).

**Table 4.21: Midline primary pressure wave sequence for GD.**

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Onset</strong></td>
<td>Peak</td>
<td>Onset</td>
<td>Peak</td>
</tr>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0.160</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.22</td>
<td>0.309</td>
<td>0.28</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.28</td>
<td>0.348</td>
<td>0.332</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.22: Relative timing of primary midline peak pressures for GD.**

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.192</td>
<td>0.208</td>
<td>0.098</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.153</td>
<td>0.170</td>
<td>0.06</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.041</td>
<td>0.042</td>
<td>0.038</td>
</tr>
</tbody>
</table>
There is no significant difference between the anterior and posterior midline with a small 3 kPa decrease in mid palatal maximum. There are also small decreases in the right anterior and left posterior channels in the region of 3 kPa (see figure 4.23 and table 4.23).
Figure 4.23: Mizone® versus honey pressure analysis for GD.

Table 4.24: Statistical significance between Mizone® and honey swallowing pressures for GD.

<table>
<thead>
<tr>
<th>Mizone® Vs. Honey p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.373</td>
<td>0.088</td>
<td>0.002</td>
<td>0.058</td>
<td>0.259</td>
<td>0.318</td>
<td>0.002</td>
</tr>
<tr>
<td>Max</td>
<td>0.005</td>
<td>0.154</td>
<td>0.004</td>
<td>0.008</td>
<td>0.007</td>
<td>0.030</td>
<td>0.001</td>
</tr>
<tr>
<td>Min</td>
<td>0.006</td>
<td>0.001</td>
<td>0.001</td>
<td>0.539</td>
<td>0.463</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>RMS</td>
<td>0.049</td>
<td>0.985</td>
<td>0.001</td>
<td>0.037</td>
<td>0.033</td>
<td>0.001</td>
<td>0.002</td>
</tr>
</tbody>
</table>

The left posterior lateral channel had a very large increase in the vicinity of 40 kPa in all pressure parameters during the honey swallowing with wide variation. Mean pressures showed a small decrease in the posterior channel. Maximum pressures showed small increases in the vicinity of 5 kPa in anterior posterior both anterior lateral and the right posterior lateral. Minimum pressures showed increasingly negative values midline with...
falls of 10 kPa anteriorly, 30 kPa in the middle and 50 kPa posteriorly. The posterior midline channel showed a large increase in RMS in the range of 12 kPa (see figure 4.23 and table 4.24).

**Swallowing duration**

There was no significant difference between swallowing durations (see figure 4.24).

![Graph showing swallow durations](image)

\[ p = 0.89 \quad p = 0.802 \]

**Figure 4.24:** Average swallowing durations for GD.
4.1.7 JF results

JF has a distinct biphasic swallowing pattern with a wide pressure range in the region of 95 kPa from -35 to 60 kPa (see figure 4.25).

**Water swallowing sequence**
Participant JF has a tight temporal relationship with the onset of pressure waves. This begins with an initial drop at the anterior midline and right anterior lateral channels. At the initiation of this anterior drop the left posterior lateral pressure begins to increase. There is a sequential onset of lateral pressure before the onset of the midline pressures.
The anterior lateral pressure falls gradually away after the initial midline pressure peaks but maintains a relative increase from baseline until after the secondary pressure wave has peaked. The posterior lateral palatal pressure displays a marked pressure elevation that increases further during the midline intermediate pressure drop, falling away on the onset of the midline secondary pressure wave. All 3 midline sensors show a distinct pressure fall relative to the lateral sensors prior to the onset of a sequential series of pressure peaks from anterior to posterior.

**Mizone® swallowing sequence**
This follows a very similar pattern to the water swallowing.

**Honey swallowing sequence**
The sequence of pressure wave onset and peaks followed the same description as the other 2 liquids.
### All 7 Channels

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 kPa</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>-40 kPa</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = .................

anterior  mid-palate  posterior  right anterior  right posterior  left anterior  left posterior

### Midline Channels

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 kPa</td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
<td><img src="image15" alt="Graph" /></td>
</tr>
<tr>
<td>-40 kPa</td>
<td><img src="image16" alt="Graph" /></td>
<td><img src="image17" alt="Graph" /></td>
<td><img src="image18" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = .................

anterior  mid-palate  posterior

### Lateral Channels

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kPa</td>
<td><img src="image19" alt="Graph" /></td>
<td><img src="image20" alt="Graph" /></td>
<td><img src="image21" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image22" alt="Graph" /></td>
<td><img src="image23" alt="Graph" /></td>
<td><img src="image24" alt="Graph" /></td>
</tr>
<tr>
<td>-25 kPa</td>
<td><img src="image25" alt="Graph" /></td>
<td><img src="image26" alt="Graph" /></td>
<td><img src="image27" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = .................

right anterior  right posterior  left anterior  left posterior

Figure 4.25: Averaged pressure profiles for JF.
Laterality and onset

JF shows relatively symmetrical lateral pressures anteriorly but shows a right posterior dominance with an increase of approximately 15 kPa. JF has a tight temporal relationship of pressure wave onset with the posterior preceding the mid channel (see table 4.25). The pressure peaks, however, show a clear sequential anterior to posterior relationship of duration in the region of 0.12 s (see table 4.26).

Table 4.25: Midline primary pressure wave sequence for JF.

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.109</td>
<td>0.12</td>
<td>0.125</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.058</td>
<td>0.06</td>
<td>0.078</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.051</td>
<td>0.06</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Table 4.26: Relative timing of primary midline peak pressures for JF.

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water (s)</th>
<th>Mizone (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.109</td>
<td>0.12</td>
<td>0.125</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.058</td>
<td>0.06</td>
<td>0.078</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.051</td>
<td>0.06</td>
<td>0.047</td>
</tr>
</tbody>
</table>
Figure 4.26: Water versus Mizone® pressure analysis for JF.

Table 4.27: Statistical significance between water and Mizone® swallowing pressures for JF

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.063</td>
<td>0.341</td>
<td>0.584</td>
<td>0.447</td>
<td>0.686</td>
<td>0.367</td>
<td>0.858</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.655</td>
<td>0.128</td>
<td>0.798</td>
<td>0.496</td>
<td>0.223</td>
<td>0.793</td>
<td>0.968</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.002</td>
<td>0.890</td>
<td>0.889</td>
<td>0.144</td>
<td>0.673</td>
<td>0.143</td>
<td>0.115</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>0.004</td>
<td>0.890</td>
<td>0.377</td>
<td>0.294</td>
<td>0.135</td>
<td>0.570</td>
<td>0.834</td>
</tr>
</tbody>
</table>

In the anterior channel there was a large fall in the range of 20 kPa for minimum pressure for the Mizone® swallows. There was also a small 5 kPa increase of RMS in the same channel for Mizone® (see figure 4.26). Otherwise there was no significant difference between the 2 liquids on swallowing (see table 4.27).
JF showed no significant differences in the anterior and left anterior channels with only a 5 kPa increase in the right anterior on Mizone swallowing (see table 4.28). The mid palatal channel showed a reduction in average maximum and RMS in the vicinity of 7 and 4 kPa respectively (see figure 4.27). The posterior channels showed a large 12 kPa increase of mean pressure value on honey and a smaller 3 kPa increase of RMS. There was a corresponding decrease of maximal pressure of 7 kPa. The lateral posterior channels all showed large decreases in mean, maximum and RMS in ranging from 8-15 kPa. Overall,

Table 4.28: Statistical significance between Mizone® and honey swallowing pressures for JF.

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.059</td>
<td>0.602</td>
<td>0.003</td>
<td>0.640</td>
<td>0.072</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.331</td>
<td>0.001</td>
<td>0.010</td>
<td>0.018</td>
<td>0.190</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.062</td>
<td>0.056</td>
<td>0.069</td>
<td>0.467</td>
<td>0.328</td>
<td>0.595</td>
<td>0.049</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>0.131</td>
<td>0.003</td>
<td>0.019</td>
<td>0.102</td>
<td>0.998</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>
there appeared to be a drop in pressure with Mizone in all channels except for the posterior midline.

**Swallowing duration**

There was no significant difference between water and Mizone® swallows however there a slight increase in duration for the honey swallowing (see figure 4.28).

![Bar chart showing average swallowing durations for JF](image)

- Water: 1.03 seconds
- Mizone: 1.02 seconds
- Honey: 1.17 seconds

\[ p = 0.83 \quad \text{and} \quad p = 0.043 \]

**Figure 4.28: Average swallowing durations for JF.**
4.1.8 JP results

JP is a predominantly positive pressure monophasic swallower with a range of 65 kPa, from -10 to 55 kPa (see figure 4.29).

**Water swallowing sequence**

JP displays a sequential elevation of the anterior then mid palatal midline. The right anterior and left posterior channels record a pressure rise whereas the left anterior and right posterior fall prior to the onset of their pressure rises. These lateral pressure wave peaks occur in close temporal proximity to each other just prior to the anterior and middle midline pressure peaks. They begin to fall away prior to the posterior midline peak, the last region to experience a pressure wave, which then also falls away smoothly.

**Mizone swallowing sequence**

JP’s Mizone swallowing follows the same sequential pattern of lateral and midline onset and peaks. Again, all the lateral regions peak just prior to the anterior midline with a sequential anterior pattern of midline peaks.

**Honey swallowing sequence**

The honey pattern shows an earlier onset of all the anterior regions. They display the same behaviour with respect to pressure rises at the right and mid anterior but a pressure drop then early rise occurs at anterior left channel. Once again the anterior mid-palate shows a double peak. The right lateral shows a gradual rise to peak whereas the left anterior and both posterior laterals peak sharply with a tight temporal onset. The anterior and posterior laterals all peak together and this is followed by the middle and ultimately the posterior midline.
### All 7 Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 kPa</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>-10 kPa</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
<td><img src="image9.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ........................

- anterior
- mid-palate
- posterior
- right anterior
- right posterior
- left anterior
- left posterior

### Midline Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kPa</td>
<td><img src="image10.png" alt="Graph" /></td>
<td><img src="image11.png" alt="Graph" /></td>
<td><img src="image12.png" alt="Graph" /></td>
</tr>
<tr>
<td>20 kPa</td>
<td><img src="image13.png" alt="Graph" /></td>
<td><img src="image14.png" alt="Graph" /></td>
<td><img src="image15.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image16.png" alt="Graph" /></td>
<td><img src="image17.png" alt="Graph" /></td>
<td><img src="image18.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ........................

- anterior
- mid-palate
- posterior

### Lateral Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 kPa</td>
<td><img src="image19.png" alt="Graph" /></td>
<td><img src="image20.png" alt="Graph" /></td>
<td><img src="image21.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image22.png" alt="Graph" /></td>
<td><img src="image23.png" alt="Graph" /></td>
<td><img src="image24.png" alt="Graph" /></td>
</tr>
<tr>
<td>-10 kPa</td>
<td><img src="image25.png" alt="Graph" /></td>
<td><img src="image26.png" alt="Graph" /></td>
<td><img src="image27.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ........................

- right anterior
- right posterior
- left anterior
- left posterior

Figure 4.29: Averaged pressure profiles for JP.
Laterality and onset

JP displays a marked asymmetry in lateral pressures with a distinct right-sided dominance anteriorly in the region of 30 kPa and a left-sided dominance posteriorly, also in the region of 30 kPa. JP has a sequential onset of pressure waves with a significant delay in the honey swallows (see table 4.29). The antero-posterior primary pressure wave peaks show a very tight anterior midline relationship in Water and Mizone® swallows with a more delayed sequential pattern in the honey swallows (see table 4.30).

Table 4.29: Midline primary pressure wave sequence for JP.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>Onset</td>
<td>Peak</td>
<td>Onset</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.246</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.202</td>
<td>0.246</td>
<td>0.3</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.243</td>
<td>0.305</td>
<td>0.336</td>
</tr>
</tbody>
</table>

Table 4.30: Relative timing of primary midline peak pressures for JP.

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.058</td>
<td>0.072</td>
<td>0.121</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0</td>
<td>0.017</td>
<td>0.055</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.058</td>
<td>0.055</td>
<td>0.066</td>
</tr>
</tbody>
</table>
Figure 4.30: Water versus Mizone® pressure analysis for JP.

Table 4.31: Statistical significance between water and Mizone® swallowing pressures for JP.

<table>
<thead>
<tr>
<th>Water versus Mizone® p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.236</td>
<td>0.982</td>
<td>0.784</td>
<td>0.990</td>
<td>0.340</td>
<td>0.922</td>
<td>0.581</td>
</tr>
<tr>
<td>Max</td>
<td>0.022</td>
<td>0.890</td>
<td>0.487</td>
<td>0.379</td>
<td>0.145</td>
<td>0.086</td>
<td>0.600</td>
</tr>
<tr>
<td>Min</td>
<td>0.176</td>
<td>0.919</td>
<td>0.552</td>
<td>0.417</td>
<td>0.266</td>
<td>0.763</td>
<td>0.521</td>
</tr>
<tr>
<td>RMS</td>
<td>0.341</td>
<td>0.417</td>
<td>0.854</td>
<td>0.260</td>
<td>0.069</td>
<td>0.457</td>
<td>0.682</td>
</tr>
</tbody>
</table>

JP showed no significant differences between water and Mizone except for a small 3 kPa increase in anterior maximal pressure (see figure 4.30 and table 4.31).
Table 4.32: Statistical significance between Mizone® and honey swallowing pressures for JP.

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.001</td>
<td>0.005</td>
<td>0.524</td>
<td>0.003</td>
<td>0.017</td>
<td>0.854</td>
<td>0.076</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.003</td>
<td>0.010</td>
<td>0.153</td>
<td>0.087</td>
<td>0.001</td>
<td>0.014</td>
<td>0.003</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.083</td>
<td>0.003</td>
<td>0.316</td>
<td>0.007</td>
<td>0.716</td>
<td>0.493</td>
<td>0.105</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>0.001</td>
<td>0.024</td>
<td>0.198</td>
<td>0.009</td>
<td>0.001</td>
<td>0.049</td>
<td>0.024</td>
</tr>
</tbody>
</table>

There was no significant difference in the posterior channel (see table 4.32). The anterior channels had a tendency to increase in pressure on increasing consistency with increases in mean and RMS in all anterior channels (see figure 4.31). The left anterior showed an increase of 13 kPa whereas the rest had modest increases in the range of 3-5 kPa. The middle channel recorded increases in all parameters. In keeping with the trend to increase pressure, the left and right posterior lateral channels demonstrated moderate (7-12 kPa) increases in maximal pressure and minor (1-2 kPa) increases in RMS.
Swallowing duration

There was no difference in duration between water and Mizone®, however there was an increase in duration of 0.32 s on honey swallows compared to Mizone® swallows (see figure 4.32).

Figure 4.32: Average swallowing durations for JP.
4.1.9 LA results

LA displays a distinct biphasic swallowing pattern. There was a subtle tertiary wave present and a marked intermediate phase between the primary and secondary pressure waves. There was a pressure range of 75 kPa between -30 and 45 kPa (see figure 4.33).

*Water swallowing sequence*

The pressure rises of the anterior and mid-palatal channels are closely followed by the posterior lateral then mid-palatal and posterior midline channels. The anterior midline and lateral channels then peak together followed by a distinct sequential posterior midline pressure wave. The intermediate pressure drop begins sequentially at the anterior palate with a repeat of the activation sequence of the primary wave. Finally, a smaller tertiary wave develops with the same sequences as the preceding waves.

*Mizone swallowing sequence*

The Mizone swallowing has the same basic sequence, however the anterior midline pressure onset and peak occur before the anterior lateral onset and peak. These are closely followed by the posterior lateral and mid-palatal channel peaks. The posterior midline has a distinct delay in onset and peak. The intermediate and secondary waves behave similarly. The tertiary wave is less distinct in the Mizone swallows.

*Honey swallowing sequence*

The anterior pressure drops as the mid-palatal and posterior pressures rise slightly before falling again. The anterior palatal pressure rise then precedes all others followed by a relatively symmetric bilateral anterior lateral pressure rise. Next, the mid-palatal pressure rise is followed by both posterior lateral channels and finally the posterior midline. There is then a distinct sequential intermediate phase with a fall in pressure beginning at the anterior midline then lateral channels. A secondary pressure wave of similar sequence to the primary then occurs. In the honey swallowing the posterior pressure wave is more variable and less defined. There is a relatively small sequential tertiary wave present as well.
### All 7 Channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 kPa</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>-30 kPa</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
<td><img src="image9.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ·······················

anterior mid-palate posterior right anterior right posterior left anterior left posterior

### Midline channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kPa</td>
<td><img src="image10.png" alt="Graph" /></td>
<td><img src="image11.png" alt="Graph" /></td>
<td><img src="image12.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image13.png" alt="Graph" /></td>
<td><img src="image14.png" alt="Graph" /></td>
<td><img src="image15.png" alt="Graph" /></td>
</tr>
<tr>
<td>-35 kPa</td>
<td><img src="image16.png" alt="Graph" /></td>
<td><img src="image17.png" alt="Graph" /></td>
<td><img src="image18.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ·······················

anterior mid-palate posterior

### Lateral channels

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 kPa</td>
<td><img src="image19.png" alt="Graph" /></td>
<td><img src="image20.png" alt="Graph" /></td>
<td><img src="image21.png" alt="Graph" /></td>
</tr>
<tr>
<td>10 kPa</td>
<td><img src="image22.png" alt="Graph" /></td>
<td><img src="image23.png" alt="Graph" /></td>
<td><img src="image24.png" alt="Graph" /></td>
</tr>
<tr>
<td>-15 kPa</td>
<td><img src="image25.png" alt="Graph" /></td>
<td><img src="image26.png" alt="Graph" /></td>
<td><img src="image27.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ·······················

right anterior right posterior left anterior left posterior
Laterality and onset

LA displays some variation in the lateral pressures developed. In the water and the Mizone there is a fairly even balance of pressure. In the honey swallowing marked right-sided posterior pressure dominance develops in the region of 20 kPa. LA displays a distinct and relatively lengthy onset of pressure waves (see table 4.33) with a well-defined sequential progression of midline pressure peaks from anterior to posterior in the vicinity of 0.13 to 0.2 s (see table 4.34).

Table 4.33: Midline primary pressure wave sequence for LA.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>Onset (s)</td>
<td>Peak (s)</td>
<td>Onset (s)</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.428</td>
<td>0</td>
</tr>
<tr>
<td>Middle</td>
<td>0.352</td>
<td>0.479</td>
<td>0.234</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.447</td>
<td>0.562</td>
<td>0.424</td>
</tr>
</tbody>
</table>

Table 4.34: Relative timing of primary midline peak pressures for LA.

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water (s)</th>
<th>Mizone (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.131</td>
<td>0.198</td>
<td>0.178</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.046</td>
<td>0.101</td>
<td>0.077</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.085</td>
<td>0.097</td>
<td>0.101</td>
</tr>
</tbody>
</table>
LA displayed no significant difference in any of the anterior and middle channels (see table 4.35). The posterior midline channel showed an increase in mean pressure of 10 kPa and a reduction in the minimum pressure by 20 kPa (see figure 4.34). In the posterior lateral channels there was a decrease in all parameters with the right being in the range of 10 kPa and the left of 20 kPa.

**Figure 4.34: Water versus Mizone® pressure analysis for LA.**

**Table 4.35: Statistical significance between water and Mizone® swallowing pressures for LA.**

<table>
<thead>
<tr>
<th>Water versus Mizone®</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.101</td>
<td>0.063</td>
<td>0.010</td>
<td>0.301</td>
<td>0.652</td>
<td>0.001</td>
<td>0.018</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.677</td>
<td>0.093</td>
<td>0.439</td>
<td>0.451</td>
<td>0.248</td>
<td>0.007</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.448</td>
<td>0.203</td>
<td>0.005</td>
<td>0.304</td>
<td>0.352</td>
<td>0.003</td>
<td>0.026</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>0.401</td>
<td>0.102</td>
<td>0.120</td>
<td>0.970</td>
<td>0.697</td>
<td>0.001</td>
<td>0.014</td>
</tr>
</tbody>
</table>
LA displayed no significant difference in the posterior channel (see table 4.36) however, a drop of the mean pressure occurred in the anterior and middle channel of 10 and 5 kPa respectively (see figure 4.35). The right anterior lateral channel displayed an overall reduction in pressure in all parameters with a reduction in mean pressure of 10 kPa and the others around 5 kPa. The left anterior had a significant reduction of mean and minimum pressure in the vicinity of 5 kPa. The left posterior channel also showed a reduction in all
parameters. The only channel that did not follow the trend of pressure reduction was the right posterior with a moderate 10 kPa increase in mean minimum and RMS.

**Swallowing duration**

There was no statistically significant difference in duration between water and Mizone® (see figure 4.36).

![Swallowing duration chart](chart.png)

- Water: 1.09 seconds
- Mizone: 0.99 seconds
- Honey: 1.20 seconds

\[ p = 0.19 \quad \text{and} \quad p = 0.025 \]

**Figure 4.36: Average swallowing durations for LA.**
4.1.10 MS results

MS displays a monophasic swallowing pattern and a predominantly positive pressure profile with a pressure range of 70 kPa between -10 and 60 kPa (see figure 4.37).

**Water swallowing sequence**

MS has an asymmetric sequence with the right anterior, mid-palate and left anterior pressure rising and holding a plateau. The anterior midline then begins to increase steadily with both anterior lateral regions rising at the same time. Both posterior regions and the mid-palatal midline rise sharply together and this is followed finally by the posterior midline. The posterior midline has a transient pressure drop just prior to the positive pressure wave. All pressure waves fall away after this posterior midline peak.

**Mizone swallowing sequence**

This swallowing follows the same pattern of onset and falling away as the Mizone swallowing with an asymmetric hold then anterior to posterior lateral then midline pressure wave.

**Honey swallowing sequence**

The honey swallowing shows a similar pattern of asymmetric left and right lateral pressure. The right anterior and left posterior channels rise in pressure as the left anterior and right posterior fall. The mid-palatal pressure rises prior to the anterior and holds a plateau. Following the initial mid-palatal pressure rise the anterior midline pressure drops briefly before a pressure rise to a preliminary peak in coordination with both anterior lateral regions. This is then followed by bilateral pressure rises at the posterior then a sharp pressure rise with the mid palatal region that peaks in concert with the posterior laterals. Finally there is a small pressure rise at the anterior midline followed by the mid palatal and lastly posterior lateral. There is a small secondary sequential swallow that follows the same sequence though at a much reduced pressure in the honey swallows.
<table>
<thead>
<tr>
<th>Channels</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 7 Channels</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>Midline Channels</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>Lateral Channels</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

Figure 4.37: Averaged pressure profiles for MS.
Laterality and onset

MS shows a lateral pressure twist with a marked right-sided preference in the anterior and left sided preference in the posterior lateral. The right anterior initially rises steeply as the left anterior falls before rising in sequence together approaching the pressure wave peak. This is similar but occurs on opposite sides in the posterior channels. MS had a distinct sequential onset of pressure waves with a marked delay between the anterior to the middle and posterior channels (see table 4.37). The primary wave peaks were very tightly grouped temporally with the middle channel peaking first and the posterior and anterior channels peaking almost simultaneously within 0.1 s (see table 4.38).

Table 4.37: Midline primary pressure wave sequence for MS.

<table>
<thead>
<tr>
<th></th>
<th>Water Onset</th>
<th>Water Peak</th>
<th>Mizone Onset</th>
<th>Mizone Peak</th>
<th>Honey Onset</th>
<th>Honey Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0.653</td>
<td>0</td>
<td>0.775</td>
<td>0</td>
<td>0.832</td>
</tr>
<tr>
<td>Middle</td>
<td>0.441</td>
<td>0.622</td>
<td>0.667</td>
<td>0.747</td>
<td>0.575</td>
<td>0.732</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.594</td>
<td>0.686</td>
<td>0.727</td>
<td>0.816</td>
<td>0.74</td>
<td>0.821</td>
</tr>
</tbody>
</table>

Table 4.38: Relative timing of primary midline peak pressures for MS.

<table>
<thead>
<tr>
<th>Primary wave peak</th>
<th>Water</th>
<th>Mizone</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0</td>
<td>0</td>
<td>-0.011</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>-0.03</td>
<td>-0.027</td>
<td>-0.102</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.032</td>
<td>0.041</td>
<td>0.091</td>
</tr>
</tbody>
</table>
Figure 4.38: Water versus Mizone® pressure analysis for MS.

Table 4.39: Statistical significance between water and Mizone® swallowing pressures for MS.

<table>
<thead>
<tr>
<th></th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.593</td>
<td>0.598</td>
<td>0.153</td>
<td>0.012</td>
<td>0.911</td>
<td>0.869</td>
<td>0.626</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.497</td>
<td>0.738</td>
<td>0.571</td>
<td>0.003</td>
<td>0.250</td>
<td>0.531</td>
<td>0.648</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.917</td>
<td>0.230</td>
<td>0.260</td>
<td>0.008</td>
<td>0.012</td>
<td>0.400</td>
<td>0.330</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>0.979</td>
<td>0.854</td>
<td>0.266</td>
<td>0.009</td>
<td>0.134</td>
<td>0.239</td>
<td>0.450</td>
</tr>
</tbody>
</table>

MS displayed no significant differences in the midline or posterior lateral channels (see table 4.39). The right anterior channel had moderate increases in all parameters around 10 kPa (see figure 4.38). The left anterior in contrast displayed slightly lower minimum pressure of approximately 3 kPa.
There were no significant differences in the middle or left anterior channels (see table 4.40). The anterior channel had a minor reduction in minimum pressure and the right anterior had a minor 2 kPa reduction in RMS (see figure 4.39). The posterior channel showed a minor increase in mean, maximum and RMS in the region of 3-5 kPa. The right
posterior also showed a minor rise in RMS and fall in minimum of around 3 kPa. Overall changes noted were of a minor nature.

**Duration**

MS had a 0.2 s increase in duration in Mizone® swallows over the water swallows and a 0.3 s increase in honey over Mizone® (see figure 4.40).

\[ \text{Figure 4.40: Average swallowing durations for MS.} \]
4.2 Generic Results

**Generic water swallowing sequence**

The anterior and lateral anterior channels begin to rise together in a tight sequential pattern with a gradual increase in pressure (see figure 4.41). Following this the lateral posterior channels begin their onset. Subsequently, all the lateral channels and the anterior channel peak in tight temporal relationship then begin to fall away. As the lateral and anterior channels are increasing in pressure the middle channel begins its pressure rise ahead of the posterior midline channel, which is the last to rise. The mid-palatal and posterior midline channels peak sequentially after the lateral channels have begun to fall away. The mid-palatal and posterior midline channels fall away rapidly after their peak to return to normal. There is a smaller secondary pressure wave that displays a similar sequential onset profile evident.

**Generic Mizone® swallowing sequence**

This follows an almost identical pattern to the water swallowing with respect to sequence and timing of onset and peaks. The smaller secondary pressure wave is also present.

**Generic honeys swallowing sequence**

Again there is a very similar pattern to the sequence and pattern of the honey-thick Mizone® swallows. The secondary pressure wave is more defined in the honey swallows. The anterior channel and all lateral channels peak as the mid-palatal and posterior channels are still dropping in pressure. The mid-palatal and posterior channels rise and peak in pressure subsequent to this. There is also markedly increased post swallowing pressure activity evident in the honey swallowing that is not seen in the previous 2 liquids. Instead of a fall to a smooth baseline there is a series of multiple pressure rises and falls in all channels.
### All 7 Channels

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kPa</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td>20 kPa</td>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
<td><img src="image9.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ···················

- anterior
- mid-palate
- posterior
- right anterior
- right posterior
- left anterior
- left posterior

### Midline Channels

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kPa</td>
<td><img src="image10.png" alt="Graph" /></td>
<td><img src="image11.png" alt="Graph" /></td>
<td><img src="image12.png" alt="Graph" /></td>
</tr>
<tr>
<td>20 kPa</td>
<td><img src="image13.png" alt="Graph" /></td>
<td><img src="image14.png" alt="Graph" /></td>
<td><img src="image15.png" alt="Graph" /></td>
</tr>
<tr>
<td>0 kPa</td>
<td><img src="image16.png" alt="Graph" /></td>
<td><img src="image17.png" alt="Graph" /></td>
<td><img src="image18.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ···················

- anterior
- mid-palate
- posterior

### Lateral Channels

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 kPa</td>
<td><img src="image19.png" alt="Graph" /></td>
<td><img src="image20.png" alt="Graph" /></td>
<td><img src="image21.png" alt="Graph" /></td>
</tr>
<tr>
<td>20 kPa</td>
<td><img src="image22.png" alt="Graph" /></td>
<td><img src="image23.png" alt="Graph" /></td>
<td><img src="image24.png" alt="Graph" /></td>
</tr>
<tr>
<td>5 kPa</td>
<td><img src="image25.png" alt="Graph" /></td>
<td><img src="image26.png" alt="Graph" /></td>
<td><img src="image27.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

1 s = ···················

- right anterior
- right posterior
- left anterior
- left posterior

**Figure 4.41:** Generic overlay pressure profile.
**Laterality and onset**

The right and left anterior lateral channels are closely matched in size. Posteriorly, however, right-sided pressure dominance exists in the group studied. There is a distinct onset of pressure waves beginning in an anterior to posterior direction in all liquid swallows (see table 4.41). There is a tight temporal relationship with the anterior and middle pressure wave peak with a more pronounced delay to the posterior pressure wave peak. The pressure peaks travel in an anterior to posterior direction with an average duration of 0.057 to 0.104s (see table 4.42).

**Table 4.41: Generic midline primary pressure wave sequence.**

<table>
<thead>
<tr>
<th>Water</th>
<th>Mizone®</th>
<th>Honey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.201</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>0.12</td>
<td>0.204</td>
</tr>
<tr>
<td></td>
<td>0.204</td>
<td>0.154</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.128</td>
<td>0.258</td>
</tr>
<tr>
<td></td>
<td>0.258</td>
<td>0.210</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.42: Relative timing of generic primary midline peak pressures.**

<table>
<thead>
<tr>
<th>Water (s)</th>
<th>Mizone® (s)</th>
<th>Honey (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior to posterior</td>
<td>0.057</td>
<td>0.063</td>
</tr>
<tr>
<td>Ant-middle</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>Middle to posterior</td>
<td>0.054</td>
<td>0.056</td>
</tr>
</tbody>
</table>

**Pressure profile difference between water, Mizone® and honey**

Superimposition of all 7 channels in water versus Mizone® shows the marked temporal similarity in pressure patterns though there is minor variation in pressure amplitudes. Channels have been individually scaled to best show this pattern. All graphs are overlaid on the same time axis at the initial mid palatal peak. There is a marked pattern of clearance swallows that can be seen following the primary pressure wave in the honey swallows that is characterised by the disturbed pressure signal (see figure 4.42 ).
Water = Blue  Mizone® =Red  Mizone® =Red  Honey = Green

Figure 4.42: Pressure profile overlay comparisons between water, Mizone® and honey.
**Overall mean of individual pressure averages**

The average pressures from each individual were combined and subsequently averaged to create the following graphs.

![Graphs showing average pressures for Water and Mizone®](image)

**Figure 4.43:** Overall mean of individual average pressures; Water versus Mizone®.

**Table 4.43:** Statistical significance between water and Mizone® for the overall mean of individual average swallowing pressures.

<table>
<thead>
<tr>
<th>Water Vs Mizone® p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.537</td>
<td>0.620</td>
<td>0.917</td>
<td>0.222</td>
<td>0.319</td>
<td>0.126</td>
<td>0.244</td>
</tr>
<tr>
<td>Max</td>
<td>0.513</td>
<td>0.967</td>
<td>0.354</td>
<td>0.220</td>
<td>0.233</td>
<td>0.569</td>
<td>0.566</td>
</tr>
<tr>
<td>Min</td>
<td>0.194</td>
<td>0.682</td>
<td>0.902</td>
<td>0.180</td>
<td>0.496</td>
<td>0.049</td>
<td>0.176</td>
</tr>
<tr>
<td>RMS</td>
<td>0.615</td>
<td>0.401</td>
<td>0.834</td>
<td>0.151</td>
<td>0.421</td>
<td>0.190</td>
<td>0.268</td>
</tr>
</tbody>
</table>

There were no significant differences in pressures (see figure 4.43 and table 4.43).
Figure 4.44: Overall mean of individual average pressures; Mizone versus honey.

Table 4.44: Statistical significance between Mizone® and honey for the overall mean of individual average swallowing pressures.

<table>
<thead>
<tr>
<th>Mizone® Vs Honey p values</th>
<th>Anterior</th>
<th>Middle</th>
<th>Posterior</th>
<th>Right Ant</th>
<th>Left Ant</th>
<th>Right Post</th>
<th>Left Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.723</td>
<td>0.457</td>
<td>0.063</td>
<td>0.945</td>
<td>0.534</td>
<td>0.282</td>
<td>0.473</td>
</tr>
<tr>
<td>Max</td>
<td>0.563</td>
<td>0.613</td>
<td>0.282</td>
<td>0.205</td>
<td>0.029</td>
<td>0.134</td>
<td>0.363</td>
</tr>
<tr>
<td>Min</td>
<td>0.282</td>
<td>0.415</td>
<td>0.944</td>
<td>0.859</td>
<td>0.328</td>
<td>0.330</td>
<td>0.761</td>
</tr>
<tr>
<td>RMS</td>
<td>0.720</td>
<td>0.587</td>
<td>0.031</td>
<td>0.225</td>
<td>0.035</td>
<td>0.185</td>
<td>0.391</td>
</tr>
</tbody>
</table>

There were no significant differences noted in the generic pressure analysis (see figure 4.44 and table 4.44).
**Swallowing duration**

On taking the overall mean of averages from each individual’s 12 swallows a significant increase in duration between Mizone® and honey-thick Mizone® was observed (see figure 4.45). The average swallowing duration from submental sEMG activation to the terminal fall in pressure on the posterior midline palate was 1.08 s for water 1.08 s for Mizone® and 1.44 s for honey-thick Mizone®.

![Mean Individual Average Primary Swallow Duration](image)

\[ p = 0.976 \quad p=0.017 \]

*Figure 4.45 Overall mean of individual average swallowing durations.*
5  Discussion

To date, there have been few published studies of the generation and coordination of absolute intra-oral pressure during the oral phase of swallowing. Consequently, there is a dearth of knowledge surrounding the forces involved during this important stage of deglutition. The present study set out, firstly, to determine if there was a common underlying pattern to the highly variable and complex absolute pressure profiles generated during discrete, liquid swallows; and, secondly, to investigate the effects of increased viscosity on these absolute intra-oral pressure profiles.

5.1 Pressure patterns

5.1.1 Generic pressure pattern

Numerous studies have reported high levels of inter-subject variability in swallowing patterns. Shaker et al. (1988) reported a wide range of inter-individual pressure profiles associated with normal videofluoroscopic bolus transit. Others have also described significant inter-individual variation in tongue movement variation (Gay et al., 1994; Tasko et al., 2002; Steele and Van Lieshout, 2009) and pressure profiles (Ono et al., 2004; Kennedy et al., 2010). Regarding intra-individual variation however, there appears to be considerable conservation of pressure patterns (Ono et al., 2004; Peng et al., 2007; Kennedy et al., 2010).

To simplify the analysis of inter- and intra-subject swallowing patterns, I developed a unique approach where I overlaid the pressure recordings of multiple swallows at a fixed point within a swallow. My initial attempts at locating a repeatable overlay point were based on the terminal mid-palatal pressure peak and as such, the terminal phases of all swallows aligned very closely. However, this resulted in the earlier stages of the swallow being lost in the overlay. By utilising a more central point of the swallow, (the peak of the initial major mid-palatal pressure rise), I found that the coordination of pressure gradients between individuals was significantly improved. By using this standardised method, I was able to overlay each individual’s pressure pattern, to construct a generic pressure
wave pattern common to all participants. This allowed me to divide standardised wave patterns into 4 descriptive stages relative to the initial major midpalatal pressure rise (see figure 5.1).

<table>
<thead>
<tr>
<th>All Seven Channels</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>70kPa</td>
<td></td>
</tr>
<tr>
<td>25kPa</td>
<td></td>
</tr>
<tr>
<td>-10kPa</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1: Generic water swallowing pressure profile.

Stage 1 Preparation. This is characterised by containment of the bolus and is highly variable in terms of pressure amplitude and duration.

Stage 2 Primary pressure wave. This involves the highly stereotyped primary pressure wave which has a defined sequential onset and offset of pressure. It begins with a sudden rise of pressure in the anterior of the mouth and terminates after a peak is reached at the posterior midline.

Stage 3 Intermediate stage. This may not be present in all individuals. It is characterised by a fall in pressure as measured at the anterior and lateral parts of the mouth, while the midpalatal and posterior midline is still experiencing the primary pressure wave. These then begin to rise in pressure as the midpalate and posterior midline pressures decline, resulting in a relative pressure gradient from the anterior and lateral margins of the tongue.
towards the midline. Following this, there is a sequential, secondary rostro-caudal midline pressure wave with the same pattern of onset as the primary wave.

*Stage 4. Terminal phase.* Here the pressures in all channels return to pre-swallowing levels.

A number of authors have suggested that stages may be applied to the swallowing process, mainly to assist in the qualitative description of swallowing and to assess the impact of variables on swallowing parameters. For instance, Pouderoux and Kahrilas, (1995) described 3 phases of intra-oral pressure; firstly, a loading phase, with a propulsive chamber of 15-35ml in volume; secondly, a propulsive phase, with rapid bolus propulsion and expulsion and finally, a clearance phase where the tongue acts in concert with pharyngeal constrictors to clear the pharynx. Chi-Fishman and Stone (1996) used electropalatography to define 4 contact stages; pre-propulsion, propulsion, full contact, and withdrawal. However, because of the limitations of electropalatography and non-contact behaviour, they were unable to record subtle changes in tongue contact pressure or multiple pressure waves. More recently, Peng et al. (2004) divided the oral phase of swallowing into 5 sub-phases as seen on M-mode ultrasound images. These they described as the shovel stage, early transport, late transport, early final and late final stages. While the stages developed in my study embrace components of all of these, differences in methodology and timing make direct comparisons difficult. It is important, therefore, to underline that stages described here relate directly to the oral phase of swallowing and characterise changes in pressure profiles generated during the average swallow.

**5.1.2 Individual analysis**

The generic swallowing stages developed here provided an excellent template for analyzing the complex variability found between individual participants across 7 channels of pressure data. Though I was able to apply the 4 stages to each individual, inter-subject variability in pressure amplitude and timing was still high. This was particularly evident in the preparatory stage. This phenomenon has also been observed in earlier studies where there has been increased similarity in contact and movement patterns in the latter stages of swallowing and increased variation in the preparatory stages. Shaker et al. (1988)
proposed the existence of the tipper and dipper type swallows with variation in the manner that the bolus is contained prior to propulsion, and Tasko et al. (2002) and Wilson and Green (2006) described an increase in similarity between individual tongue movements in the propulsive stages of the swallow.

I decided to further sub classify individuals based on their basic swallowing patterns within each of the 4 stages given above. Not only did this result in significantly improved descriptive analysis of individual swallowing patterns but also in a simplified descriptive analysis of changes to individual swallowing patterns with bolus variation.

**Preparatory phase (Stage 1)**

Of the 4 phases, this was the most variable between subjects. Notably, I found 2 different preparatory behaviour patterns which are similar to those previously described by Shaker et al. (1988) and Dodds et al. (1989). These authors used videofluoroscopy to visualise the bolus and tongue movement whilst concurrently measuring pressure patterns generated at 2 midline pressure sensors. Their swallowing descriptions were differentiated mainly by the position of the tongue tip at the start of each swallow. In what they referred to as a tipper type swallow, the bolus was held on the dorsum of the tongue at the level of the incisors. In contrast, the so-called dipper type of swallowing was characterised by the bolus initially being held below the tongue, and then being lifted onto the tongue dorsum. Shaker et al. (1988) described the tipper type pressure pattern as a sequential positive pressure wave from the onset of swallowing and the dipper swallow as an initial positive pressure hump in the midpalate followed by a fall and subsequent rise. This pattern was generated as the mid tongue arched up while the anterior tongue scooped forward and down, then up and back as it captured the sublingual bolus.

In the present study 2 major pressure patterns of anterior and midpalatal midline were shown to exist. Here, in the tipper profile, the anterior and midpalatal channels displayed an increasing positive pressure during the preparatory phase prior to the primary pressure wave. This was evident in 7 of the participants (BA, BE, CL, CM, JP, LA and MS). In contrast, the midpalatal channel of the dipper profile maintains or rises in pressure as the anterior midline channel concurrently falls and rises before entering the primary propulsive stage. This pattern was found in only 3 of the participants (DK, JD and JF). A typical example of a tipper and dipper anterior channel, preparatory phase profiles is
shown by CL and JF respectively (see figure 5.2). The relative frequency of 70% tipper and 30% dipper is similar to the frequencies reported by (Dodds et al., 1989).

<table>
<thead>
<tr>
<th>Water CL “Tipper”</th>
<th>Water JF “Dipper”</th>
</tr>
</thead>
<tbody>
<tr>
<td>40kPa</td>
<td>60kPa</td>
</tr>
<tr>
<td>0kPa</td>
<td>0kPa</td>
</tr>
<tr>
<td>-10kPa</td>
<td>-40 kPa</td>
</tr>
</tbody>
</table>

1 second = ................
anterior mid palate posterior

Figure 5.2: Tipper and Dipper water swallowing pressure profiles.

*Primary propulsive phase (Stage2)*

Cook et al. (1989) reported that whereas the initial pattern of swallowing behaviour could be characterised by tipper and dipper activities, the behaviour of the remainder of the swallow was found to be stereotypical. This was similar to the behaviour of our subjects, where marked inter-individual similarity of the primary pressure wave followed the highly variable preparatory phase. I observed a sequential positive pressure wave that proceeded in an anterior-posterior direction as previously described by others (Dodds et al., 1990; Kahrilas et al., 1993; Pouderoux and Kahrilas, 1995; Hiiemae and Palmer, 2003). Within the highly concordant primary pressure wave there was marked inter-individual variation in the delay between the onset of the anterior midline pressure wave to the onset of the more posterior channels. However, regardless of individual temporal variation in the time of onset, the basic underlying sequential elevation from anterior to posterior was present in all subjects. Precise temporal analysis of the delay between individuals was not possible using each subject’s average swallow graph.

Two temporal patterns characterised the midline pressure peaks of the primary propulsive phase. These were described as *rollers* and *slappers* (see figure 5.3). Rollers displayed an orderly sequential midline pressure wave from anterior to posterior with a duration of
approximately 0.1 s. Examples of this pattern are CL, DK, GD, JF, JP and LA. The slappers on the other hand, tended to have a tight temporal relationship between the anterior and posterior pressure peaks of less than 0.05 s, and the middle channel usually peaked before the anterior channel. Subjects with this peak pressure pattern were BA, BE, CM, and MS.

Figure 5.3: Roller and Slapper pressure profiles.

The intermediate phase (Stage 3)

As describe earlier, the intermediate phase is not necessarily found in all subjects. I used 2 descriptive terms to characterise swallowing pressure profiles during this phase; monophasic or biphasic. In monophasic swallowers, the primary pressure wave was followed by the terminal phase. In the biphasic swallowers, however, the primary pressure wave was followed by the intermediate phase before passing back into the universal terminal phase. In other words, monophasic swallowers did not show an intermediate phase. When present, however, the intermediate phase was defined by a sequential fall in pressure followed by a secondary sequential pressure wave. Other researchers have also described the presence of biphasic swallowing pressure patterns where there are secondary peaks in the pressure profile at various regions of the oral cavity (Shaker et al., 1988; Nicosia et al., 2000; Steele et al., 2010). These authors noted the presence of biphasic peaks that varied between subjects and recording locations. Shaker et al. (1988) found these only in the anterior region. Nicosia et al. (2000) and Steele et al. (2010) also
noted that biphasic pressure peaks varied between individuals as well as midline locations (anterior, middle and posterior palate). However, because they used air filled bulbs to measure pressure they could not measure absolute intra-oral pressure. A similar inter-individual variation existed in this study; however, in contrast to the previous studies, the biphasic pattern, when present was evident in all channels. In my study, a biphasic pattern (see figure 5.4) was noted in 5 out of 10 subjects (BE, CL, CM, JF and LA), with the other 5 showing a single sharply defined monophasic pressure wave (BA, DK, GD, JP and MS) (see figure 5.5).

Figure 5.4: Biphasic pressure profiles.

Figure 5.5: Monophasic pressure profiles.
Terminal Phase (Stage 4)

In all participants, the terminal phase of the water swallowing was a clearly defined return to pre-swell resting pressure levels (see figure 5.6). This was typified by an initially sharp fall in pressure that leveled out gradually. In some cases secondary clearance swallows were performed which appear as an uneven fall of pressure on the generic and individual average graphs. The presence of secondary swallows was highly variable between individuals however their analysis is beyond the scope of this study.

Figure 5.6: Midline channel terminal phases. Terminal phase indicated by black arrow

5.2 Pressure profile effects

5.2.1 Effects of mild flavour on pressure profile and duration

To assess the effects of viscosity on pressure patterns, I initially attempted to use water and thickened water to minimise confounding factors introduced by taste. However, several subjects found plain, thickened water so unpalatable that the gag reflex was initiated. Consequently I introduced a mildly flavoured liquid (Crisp Apple flavoured Mizone®), which resulted in significant improvements in palatability at thicker consistencies.
The aim of using a mildly flavoured low-viscosity liquid was, therefore, to improve palatability in the thickened liquid not to assess the effects of taste on swallowing pressure patterns. However, in order to add to the existing data set of water swallows I used water as well as flavoured water swallows. As such, in order to describe potential confounding effects of mild flavour on pressure patterns, I analysed the swallowing stages as well as overall swallowing duration of primary pressure wave peaks. The relative viscosity of the 2 liquids was almost identical (at 25°C and a strain rate of 50/s, water and Mizone® had a viscosity of 8 cP and 17 cP respectively).

The generic pressure profile overlay revealed no descriptive difference between the 2 liquids in any of the 4 pressure profile stages (see figure 4.42 in results section). However, at an individual level there were some minor differences in patterns of intra-oral pressure observed in 4 out of 10 subjects. All differences were observed in the preparatory phase and consisted of slight changes in the onset of pressure wave initiation in the case of CL, CM, GD and MS. None of these changes resulted in a change in duration of the swallow.

Other studies that have specifically assessed the effect of taste on swallowing behaviour and used increasingly strong samples from the 4 main taste groups; sour, salty, bitter and sweet. Ding et al. (2003) showed that that submental sEMG activation was earlier in the sweet, salty and sour boluses when compared to water. However, they could not comment on oral transit time. Leow et al. (2007) noted increases in swallowing duration in the anterior preparatory phase with salty, sour or bitter liquids when compared to those that were sweet or unflavoured.

In this study, to assess swallowing duration, I used the onset of submental sEMG activity for initiation, and the last major inflexion of the fall in posterior midline pressure for termination. Direct comparison of swallowing durations from this study to those of other swallowing studies is complicated by variations in methodology and markers of initiation and termination.

The average duration from the individual best-fit swallow graphs was 1.08 s for both water and Mizone®. This compares well with the mean derived from the average of all 12 individual swallows, which was 1.10 and 1.07 s respectively. The range of the individual
mean durations was 0.7 to 1.77 s. As noted previously, I have observed significant inter-individual differences in preparatory behaviour (dipper and tipper) as well as propulsive phases (mono- and biphasic propulsive waves). The difference in the duration between individuals was mainly due to variation between these 2 stages. The tipper swallows averaged 1.00 s and the 3 dippers averaged 1.27 s resulting in a difference of approximately 0.3 s. This was slightly less than the difference reported by Dodds et al. (1989), who found that swallowing duration was approximately 0.4 to 0.5 s longer in the dipper swallows. In this study, the intermediate phase, when present, also added approximately 0.3 s to swallowing duration as derived from the average duration from primary to secondary peak of the posterior midline channel. However, the majority of the difference in swallowing duration between individuals appeared to result from a delay in initiating the primary pressure wave from the onset of the submental sEMG. Cook et al. (1989) in their manometric, submental sEMG and videofluoroscopic study, also described hesitancy in initiating lingual peristalsis as the major delaying factor in swallow duration.

At an individual level, 9 out of 10 subjects had no statistical difference in swallowing duration between the 2 liquids, the single exception showed an increase of 0.22 s. As an aim of this study was to specifically avoid strong flavour it would be interesting to enquire if this individual (MS) was a “Supertaster”, who describe all tastants (salt, sweet, sour, bitter) as more intense than those of normal tasters (Bartoshuk et al., 1994; Duffy et al., 2003). The mild levels of sweetness in the Mizone® would have been relatively more intense for such an individual, possibly eliciting a greater challenge to swallowing behaviour. Further research into effects of taste on swallowing patterns and duration should include this assessment.

The generic overlay was not suitable for assessment of the pressure profile duration due to the wide individual variation in primary pressure wave onset in each channel. However, it did allow comparison of the time between midline primary pressure wave peaks. In the case of the generic composite graph this was 0.057 s for water and 0.063 s for Mizone®. The overall average duration of individual average graph durations was 0.098 s for water and 0.102 s for Mizone® (see figure 5.7). This gives an indication of the relative inaccuracy of the generic overlay for durational studies.
5.2.2 Effects of increased viscosity on pressure profile and duration

Increasing the viscosity of Mizone® to honey-thick consistency had significant effects on the generic swallowing pressure patterns as well as their duration. Changes were observed in the preparatory, intermediate and terminal phases. Compared to that of Mizone®, the honey-thick generic overlay revealed a prolonged and flattened anterior channel pressure profile during the preparatory phase, a more distinct intermediate phase, and a less defined terminal phase.

At an individual level there were also significant changes observed in the patterns of intra-oral pressure during the preparatory phase as viscosity was increased. In low-viscosity liquids I categorised 7 out of 10 subjects as tipper swallowers. This proportion changed markedly with the introduction of honey-thick liquid as the dipper pattern now became dominant. Four of the original tipper swallowers (BA, BE, LA and MS) converted to dipper pressure patterns. The black arrows in figure 5.8 highlight examples of this change in behaviour in participants LA and MS.
Figure 5.8: Viscosity induced preparatory phase change (dipper profile indicated by vertical black arrows).

A possible explanation for this observation is that increased manipulation for preparation and containment of the more viscous bolus was required prior to the onset of the primary pressure wave.

There was no change in the behaviour of the primary propulsive wave pattern with increased bolus viscosity.

As previously mentioned, the intermediate phase of the generic swallow became more distinct with honey-thick Mizone®. Analysis at the individual level revealed the source of this change. In the preparatory phase 3 subjects (BA, BE and GD) converted from a monophasic swallowing pattern to a biphasic pattern as viscosity increased. Participant GD displayed a dramatically increased intermediate phase with smaller secondary propulsive wave present in the anterior and mid-palatal channels. Participant BA developed a distinct intermediate phase with its secondary propulsive wave across all channels, whilst BE developed a significant anterior midline and anterior lateral intermediate phase. This is illustrated in figure 5.9 where the intermediate phase peaks and troughs of GD and BA are highlighted by black arrows.
Figure 5.9: Viscosity induced development of intermediate phase peaks and troughs (indicated by vertical black arrows).

A likely explanation for this is an increase in the difficulty of clearing the residue from a more viscous bolus from the oral cavity. However, for the majority of participants (7 out of 10), there was no difference in the pattern of pressure profile observed following the primary pressure peak. This indicated that there was a highly individualised adaption to changes in viscosity. Other authors have also described an increase in double-peaked pressure patterns with increasing viscosity. Nicosia et al. (2000) noted an increased frequency with age as well as viscosity and this was interpreted as being due to an increase of effort required for bolus propulsion. In a young, healthy population Steele et al. (2010) also reported an increase in double and triple peaked swallows with increased viscosity. They suggested that this was due to insufficient pressure being generated for propulsion of the more viscous liquid compared to that of water.

The pressure fall during the terminal phase of the honey-thick generic overlay was more irregular than those of the lower viscosity liquids. Again, this was due to individual differences in swallowing behaviour. Three subjects (DK, LA and MS) showed evidence of low amplitude pressure waves in the terminal phase of the swallow. These observations suggest small, clearing movements of the tongue. In the case of DK and MS this was a secondary wave (see figure 5.10), but in the case of LA this resulted in a tertiary peak disrupting the terminal phase (see figure 5.11). This small clearance wave observed in the terminal part of the swallow is likely due to the residual, more viscous, bolus material being cleared from the oral cavity into the oropharynx. The fact that it was present in only 3 out of 10 subjects further highlights the marked individual response to changes in viscosity. This again fits with the findings of Steele et al. (2010) who reported increased tertiary pressure peaks in their nectar-thick pressure profiles. They did not, however,
analyse the swallowing pattern by phases, and as such, it is not clear where their pressure peaks occurred within the overall swallowing process.

Figure 5.10: Terminal phase clearing wave (black arrows indicate the clearance wave in the terminal phase).

Figure 5.11: Terminal phase clearing wave resulting in a minor tertiary peak (as indicated by black arrow)

At a group level, the average swallowing duration was significantly increased in the honey-thick liquid where an average increase from 1.08 to 1.44 s was observed. This finding is in concordance with several other studies (Sugita et al., 2006; Taniguchi et al., 2008; Steele et al., 2010). At the individual level, however, the durational effects of viscosity were highly variable. While some subjects showed no statistical difference in duration (CM, DK, and GD), others more than doubled their duration (BA and BE). When present, this change was most often found to be due to an increased delay from the submental sEMG initiation to the onset of the primary pressure wave. Other authors have also reported similar findings. Sugita et al. (2006) studied submental sEMG activation and
subsequent anterior midline lingual pressure onset and found that there was a delay associated with increasing consistency. Taniguchi et al. (2008) analysed submental sEMG onset and bolus transit concurrently with anterior and posterior tongue pressure. They too found a delay in onset and duration of oral bolus transit due to prolonged anterior preparation time. Most recently, Steele et al. (2010) showed that the duration of the pressure rise increased significantly in nectar-thick versus water swallows in the anterior and medial bulb locations. It is worth noting that their so-called nectar-thick liquid was actually honey-thick according to the National-Dysphagia-Task-Force (2002) as it had approximately the same viscosity as that of this study (500 cP at 25 °C and a strain rate of 50/s).

Comparing the difference in swallowing duration between individuals, it is interesting to note that the 3 subjects that displayed dipper swallows in low-viscosity liquids experienced minimal (0.15 s, JF) or no change in their swallowing durations. This suggests that in those individuals that changed pattern, the change to a dipper pattern for bolus containment accounted for a large portion of the durational change. This fits with the findings of an 0.4 to 0.5 s increase in oral phase duration from the submental sEMG spike associated with the dipper type swallowing described by Cook et al. (1989). Though Cook et al. (1989) and Dantas et al. (1990) both reported a strong correlation of lingual pressure to the submental sEMG burst, other more recent researchers have shown a poor correlation between tongue tip touching palate and the submental sEMG burst (Taniguchi et al., 2008; Lenius et al., 2009). Taniguchi et al. (2008) and Lenius et al. (2009) both suggested that some anterior tongue movement might not have been picked up by the submental sEMG onset. This reported poor correlation to submental sEMG and lingual pressure might help explain the wide range of durational changes found with increased viscosity in this study.

Figure 5.12 illustrates the average duration of the combined average individual primary pressure waves peaks from anterior to posterior. No significant difference was observed. The wide standard deviation resulted from the difference in behaviour between the roller and slapper sub-classification. At an individual level there were no changes in classification noted.
5.3 Intra-oral pressures

Considerable variation exists between studies describing intra-oral pressures, thus making direct comparison across studies difficult. Methodological differences such as sensor type and location, bolus consistency and swallowing protocol vary considerably between studies and likely account for the majority of these observed pressure differences. Pouderoux and Kahrilas, (1995) described the variation observed between different sensor types in their comparison of strain gauge and air-filled bulb sensors. They found that bulb sensors recorded positive pressure increases earlier, had a lag of onset and offset, and also registered higher peak pressures when compared to the strain gauge results. Other studies that used similar air filled bulb sensors and swallowing volumes on different boluses also showed marked disagreement between intra-oral pressures. Nicosia et al. (2000) used a strip of 3, 13 mm diameter air-filled bulbs to analyse thin liquid barium swallows of 10 ml whereas Youmans et al. (2009) used a hand held IOPI, on 10 ml swallows of multiple consistencies. Despite similar methodologies, the anterior maximal pressure values of Youmans et al. (2009) were nearly double those of Nicosia et al. (2000).

Several recent intra-oral pressure studies have used 3, 5 mm x 5 mm midline air-filled bulb sensors with the Kay PENTAX Swallowing Workstation™(Pelletier and Dhanaraj, 2006; White et al., 2009; Abdul Wahab et al., 2011). These investigations are unlikely to
be directly comparable to the present study due to the relative bulk of the fixed-volume sensors when compared to the low profile sensors used in this study. It is suggested that the method of adhesion may also result in a disruption to sensory feedback, as in at least 2 studies using the triple bulb system, significant gagging was shown to occur on placement of the most posterior bulb (Pelletier and Dhanaraj, 2006; Abdul Wahab et al., 2011). Finally, the air-filled bulb system is not able to record pressure activity at all sensors in all swallows (Steele et al., 2010). These factors result in an incomplete analysis of pressure patterns when compared to the absolute pressure readings consistently recorded at all channels and all swallows in this study.

Whereas the timing and polarity of pressure patterns in this study were relatively consistent between individuals, the analysis of pressure amplitude was complicated by large inter-individual variation. This considerable variation has been noted in several other intra-oral pressure studies (Shaker et al., 1988; Youmans and Stierwalt, 2006; Kennedy et al., 2010; Steele et al., 2010)

### 5.3.1 Holding pressures

Though the recordings were zeroed to atmospheric pressure immediately prior to bolus delivery, our pressure readings were not at zero prior to the preparatory phase due to the bolus being held before the command to swallow. I was able to observe that the regional and absolute pressures under which the boluses were held prior to swallowing varied widely between participants. Some subjects displayed a sub-atmospheric holding phase (DK, LA) whilst others were almost completely under positive pressure (BA and CM).

### 5.3.2 Maximum pressures

The combined mean of individual average maximum pressures in this study were 32.0, 38.7 and 40.8 kPa for anterior mid-palatal and posterior channels respectively. The anterior midline pressure was similar to that reported by Youmans et al. (2009), who used an anteriorly placed single IOPI air-filled bulb. However, they were higher than those reported by other authors. Shaker et al. (1988) reported pressures of 22.1 and 30 kPa at the anterior and mid–palate and Ono et al. (2004) averaged 25.6, 22 and 20 kPa for anterior,
middle and posterior palatal midline pressures. Previous studies have reported markedly different regional variations in midline peak pressure generation. Again, methodologies differ, as do sensor locations. In the present investigation, the overall average maximal pressure increased from anterior to posterior in all viscosities. This is in agreement with the findings of Nicosia et al. (2000) and White et al. (2009). Steele et al. (2010) also reported a similar midline pressure differential, though only in their high-viscosity liquid. In contrast, other studies have reported the highest maximal pressures in the anterior region; Pouderoux and Kahrilas, (1995) using strain gauges, Pelletier and Dhanaraj (2006) using the triple bulb system and Ono et al. (2004) and Hori et al. (2009) using low profile positive pressure sensors. This highlights the difficulty in attributing any single pattern of regional pressure difference to the average swallow.

The marked variation in regional pressure differential between studies is echoed by the individual intra-oral pressure results of this study. I was able to describe 3 basic regional midline patterns. The most common was similar to the overall average reported in this study, with an increase of pressure from anterior to posterior (BA, DK, LA and JF see figure 5.13). However, some participants showed maximum pressure anteriorly (BE (water) and CM see figure 5.14), whilst others displayed a rise from the anterior to mid palatal midline followed by a reduction in pressure at the posterior channel (CL, GD and MS see figure 5.15).

![Figure 5.13: Greatest maximal midline pressures posteriorly.](image-url)
5.3.3 Minimum pressures

Analysis of mean individual minimum pressure data again showed wide variation. According to the generic average graph, the regions where the greatest negative pressure developed were the anterior midline, left anterior and posterior midline channels. The posterior lateral channels displayed the least tendency to develop negative pressures. As with the maximal swallowing pressure there was considerable inter-individual variation. In most subjects the negative pressures developed in the preparatory phase or in the intermediate phases of swallowing.
5.3.4 Pressure range

A wide variation in overall swallowing pressures was noted. Some subjects generated largely positive pressures in all phases of swallowing (BA, BE and MS), whilst others (DK) developed significant negative pressures. Some displayed high maximal swallowing pressures (CM and JF), and others showed much lower pressure maxima (JP and DK). Despite this variation, the overall pressure range between highest and lowest pressure recorded from each subject’s average overlay graph was relatively consistent, being approximately 80 kPa. The narrowest average range recorded was 65 kPa (in subject JP) and the widest was 95 kPa (GD and JF). This suggests that although individuals exhibit large differences in mean swallowing pressures, the overall range of pressures developed in young healthy individuals is reasonably constant.

5.3.5 Mean pressure and root mean squared (RMS)

Maximal and minimal pressures were not able to demonstrate the changes throughout all phases of the swallow. In monophasic and largely positive pressure swallowers (e.g. MS and BA) the mean pressure gave a reasonable account of the work done during intra-oral pressure generation. However for those participants that developed a marked biphasic pattern or negative pressures (e.g. JF or LA), the average mean pressure became less indicative of overall work done. This is illustrated in the comparison of the mean graphs of MS and JF (see figure 5.16). Considering mean pressures only, it appears that MS has the largest overall pressure during the swallow, when in fact it was JF who developed considerably greater overall pressure changes during the swallow.
Due to the incorporation of negative pressure values, average regional RMS patterns were often different to those of the average mean pressures which tended to follow the patterns of the pressure maxima. Using RMS at an individual level allowed comparative analysis of changes in overall work done throughout the entire swallow, in all variations of pressure generation. Reliance on mean pressures alone would have lead to markedly inaccurate assessments of work done on the bolus in many individuals.

5.3.6 Laterality

With respect to lateral pressures, the major finding was one of marked asymmetry in pressures and again, significant inter-subject variation. No subjects displayed symmetrical pressure along the entire lateral margin during their discrete swallows. This is similar to the studies by Proffit et al. (1964) and Miller and Watkin (1996) who reported significant asymmetry of lateral pressure. Ono et al. (2004), using positive pressure sensors in a similar arrangement as this study, found no evidence of asymmetry in 10 subjects. From a generic average point of view, I also found no difference in the posterior tongue but did note distinct right anterior pressure dominance. It appears that the left and right dominance variation of the posterior channels was relatively evenly distributed, whereas
the right anterior channel appear to be more dominant due to the absence of left sided anterior dominance in our study population.

Comparing individual results I found that in the anterior lateral channels, 6 out of 10 subjects showed relatively equal pressures on the left and right with the other 4 displaying a right-sided dominance (CL, GD, JP and MS). It is interesting to note that all of those with marked anterior right-sided preference showed a corresponding marked preference of the left side posteriorly. This must have resulted from a relative twisting pattern antero-posteriorly at the lateral margins. Of the 6 subjects that displayed relatively equal anterior pressures, all had a right-sided dominance posteriorly. Though there was marked lateral asymmetry of pressure levels, the timing of onset and offset of peaks and troughs was found to remarkably symmetrical.

5.3.7 Effects of taste on absolute intra-oral pressure generation

As previously stated, the objective of using a mildly sweetened and flavoured liquid was to minimise the effects of taste at low-viscosity, whilst improving overall palatability at increased viscosity. A study that specifically looked at the effects of taste on midline swallowing pressure found that palatability itself had no significant effects on pressure generation but, relevant to this study, did find that moderate sucrose high salt and high citric acid liquids increased anterior lingual pressure (Pelletier and Dhanaraj, 2006). Another recent study employing similar midline air-filled bulbs investigated the effects of sour tastants on midline swallowing pressure and found increased pressure with sour tastants (Abdul Wahab et al., 2011).

In this study, however, the average pressure profile showed no significant difference between water and Mizone® in pressure generated at the generic level. Individually, however, 2 of the 10 subjects did show a difference. Both BA and BE showed reductions in maximum pressure with the flavoured liquid, but varied with respect to channels affected (See figure 5.17). Both showed a large increase in anterior lateral pressure (on opposite sides). The tendency towards a reduction of maximal pressures with flavoured liquids, noted in these 2 individuals, is in contrast to the findings reported by Pelletier and
Dhanaraj (2006) where flavoured liquids resulted in increased maximal swallowing pressures.

Figure 5.17: Effect of mild flavour on average maximal intra-oral pressure.

The other subjects all showed minor regional changes with 4 showing minor increases in pressure values at various channels (DK, JF, JP and MS) and the remaining 4 showing various regional decreases. The most important observation was that each individual was affected differently and no pattern of regional affect was noted. To summarise, the effects of Mizone® on swallowing pressure were minor and unique to each individual.

5.3.8 Effects of viscosity on absolute oral pressure generation

The effects of increased consistency and viscosity on swallowing pressure have been studied extensively (Kydd and Toda, 1962; Proffit et al., 1964; Shaker et al., 1988; Dantas et al., 1990; Miller and Watkin, 1996; Poudreux and Kahrilas, 1995; Nicosia et al., 2000; Sugita et al., 2006; Taniguchi et al., 2008; Steele et al., 2010). Most studies have investigated maximal pressure generation and have used different methods to measure intra-oral pressure. Direct comparison between bolus characteristics is complicated, as many studies have utilised barium, which is a highly dense liquid (Dantas et al., 1990; Shaker et al., 1988; Nicosia et al., 2000), or used foods of undisclosed viscosity (Poudreux and Kahrilas, 1995; Sugita et al., 2006). Three recent studies have focused specifically on the effects of honey-thick liquids, similar to those in this study, with viscosity in the region of 500cP (Youmans and Stierwalt, 2006; Steele et al., 2010; Youmans et al., 2009).
Most studies have reported that increasing consistency or viscosity resulted in an increase in maximal oral pressures (Kydd and Toda, 1962; Proffit et al., 1964; Shaker et al., 1988; Dantas et al., 1990; Miller and Watkin, 1996; Pouderoux and Kahrilas, 1995; Nicosia et al., 2000). Other authors have reported regional variation in intra-oral pressure generation (Sugita et al., 2006; Taniguchi et al., 2008). Both authors used 2 pressure sensors and found no increase in the anterior midline with increasing consistency, but an increase in posterior maximal pressure. Of the 3 studies that used similar viscosity liquids to the present study, Youmans and Stierwalt (2006) observed a minor increase in maximal pressure of 2 kPa using a handheld IOPI in the anterior midline region. Though statistically significant, they questioned the clinical relevance of this finding. In a subsequent study, Youmans et al. (2009) reported increased pressures in their younger sample only, and no changes in their aged groups. Finally, Steele et al. (2010) found no statistically different maximal amplitude increases in their study of water versus nectar-thick (equivalent to NDD honey-thick) liquids.

In our subjects, the overall mean of the individual averages for maximum, minimum, mean and RMS intra-oral pressure showed no statistically significant effects for increasing viscosity. This is not surprising considering the large inter-individual variation previously reported in this study. These results concur with those of Steele et al. (2010) and the aged sample of Youmans et al. (2009). In line with the uniquely individual pressure responses to the effects of flavour, there was an equally wide variety of intra-oral regions, and ranges of response to increased viscosity. However, most individual changes were small, in the region of 2 to 4 kPa. This is similar to the average findings of Youmans and Stierwalt (2006) and, therefore, of questionable clinical significance. The subjects that showed a generalised significant regional increase in pressures included BA, BE and JP. An example of BE is shown in figure 5.18.
Figure 5.18: Increase in maximal intra-oral pressure with increased viscosity.

However, unlike the increases in intra-oral pressures reported with increased viscosity in previous studies, in certain individuals (CL, JF and LA), a significant decrease in maximum and RMS intra-oral pressure was unexpectedly observed. This is illustrated by LA in figure 5.19. There is less effect with the temporally static maximum pressure in LA and CL. Importantly; all 3 participants show greater reductions in RMS, which is a measure of oral pressure generation throughout the entire swallow. The remaining subjects showed minimal generalised changes with unique individual responses to viscosity.

Figure 5.19: Reduction in maximal intra-oral pressure with increased viscosity.

As discussed earlier, RMS gives an indication of overall work done during the entire swallowing process and takes into account all stages of the swallow. Analysing individual results for RMS, significant increases were found in the posterior midline channel in 7 out of 10 subjects (including JF who showed a reduction in all other channels). Only CL
showed a decrease and the remaining 2 showed no difference. Although these findings regarding RMS approximate those of Sugita et al. (2006) and Taniguchi et al. (2008) when using maximal pressures alone, this pattern is lost as only 4 participants showed significant increases in hind palate pressure.

5.3.9 Individual pressure variation

(Youmans and Stierwalt, 2006) found that despite corresponding increases in pressure with increasing viscosity, the pressure patterns of low-pressure swallowers and high-pressure swallowers were conserved. Similarly, we found that the effects of viscosity and taste were highly conserved within individuals with high- medium- and low-pressure swallowers maintaining their patterns with increased bolus viscosity.

Pressure maxima can only describe discrete events within the entire swallow such as the peak primary wave pressure. To improve the usefulness of these measures some authors have converted raw maximal swallowing pressure data to a percentage of a maximal tongue pressure task. This ratio between normal and maximal swallowing pressures has been termed the “swallow reserve” (Huckabee and Steele, 2006; Steele et al., 2010; Youmans et al., 2009). This is intended to indicate the potential pressure generation available to the individual beyond that required completing a swallow. Steele et al. (2010) described their subjects’ maximal swallowing pressures as a percentage of a universal maximal tongue press value unrelated to the individual. However, using a generic or average reference is likely to be less meaningful than that of an individual’s. Additionally, a physiologically similar task such as a maximal effort swallow to generate this percentage rather than the physiologically different maximal tongue press would be worth investigating for future studies.

Assessment of the effects of swallowing interventions based on group averages gives, at best, a guide to expected results. However, as this study has clearly shown, individual responses are highly variable and at times opposite to the average response. This casts some doubt on using average findings in the management of individuals with dysphagia. It also highlights the need for a greater understanding of the swallowing patterns produced throughout the entire oral stage of the swallow. Considering that pressure generation is markedly variable and unique to the individual, temporally static measures give a
relatively poor assessment of the overall intra-oral pressure behaviour from preparation to terminal phase. More research into absolute pressure generation and RMS in the paediatric, geriatric and dysphagic populations is required.

5.4 Bolus dynamics

The aim of dysphagia treatment is to achieve safe and timely movement of the bolus from the oral cavity to the stomach. This requires application of a force of sufficient magnitude, polarity and importantly timing. Due to the inability to observe bolus flow in this study, consideration of oral bolus transit with respect to the pressure profiles described in here is purely speculative. Discussion, therefore, is based on extrapolation of bolus flow dynamics and lingual behaviour from other studies utilising concurrent pressure analysis and videofluoroscopy. Shaker et al. (1988) described the bolus being propelled ahead of the point of lingual to palatal contact and in all instances the major positive deflection of the palatal pressure wave occurred precisely at the same instant as lingo-palatal contact. Significantly, they also showed that negative pressures recorded at the mid-tongue coincided with movement of the tongue away from the palate.

Cook et al. (1989) published further similar research comparing manometric midline positive pressure waves during videofluoroscopy of the tongue during bolus transit. They also showed that the passage of the bolus tail and the upstroke of the peristaltic pressure wave occur practically coincidentally, with mean variation of 0.01 s. The passage of the bolus tail was also closely associated with the onset of peristaltic pressure wave by Dantas et al. (1990) who reported a range +/- 0.1s. Recently, Taniguchi et al. (2008) using videofluoroscopy and midline palatal pressure sensors found a correlation with passage of the bolus through the palatal fauces and peak posterior tongue pressure. Cook et al. (1989) described the head of the bolus entering the pharynx approximately 0.2-0.3 s ahead of the bolus tail. Taniguchi et al. (2008) also described initiation of bolus head movement beginning with the tip of the tongue touching the anterior hard palate. Based on these studies the bolus head is likely to have begun its caudal movement within 0.2-0.3 s of the peak of the primary peristaltic wave.
By dividing the average generic swallowing pattern into 4 stages and considering the earlier research described above, I have attempted to correlate the pressure profile to bolus movement. During the preparatory phase an initial increase in pressure anteriorly and laterally occurs prior to the onset of the midline positive pressure wave. This pressure pattern fits with the concept of the bolus being held in the midline groove by anterior and lateral tongue margins before a sequential positive pressure wave proceeds in a posterior direction. This description has been put forward by several authors including Dodds et al. (1990), Kahrilas et al. (1993), Poudreux and Kahrilas (1995) and Hiiemae and Palmer (2003). This positive pressure wave pattern also occurs in the primary pressure wave described in this study. Based on the bolus positions described by Shaker et al. (1988), Cook et al. (1989) and Dantas et al. (1990), it is reasonable to expect that the bolus tail has a close association to the primary pressure wave described in this study. As such subsequent pressure waves are likely to be involved with clearance of any bolus residue from the oral cavity.

I was able to describe an apparent clearance mechanism required by some individuals to clear the bolus. This was manifest by an intermediate phase. Conceivably, during the intermediate phase, remnants of the initial bolus would be gathered into the lingual midline as the anterior and lateral tongue applied pressure and the middle and posterior palatal midline had a concurrent fall in pressure. This was then followed by a secondary midline pressure wave. This secondary pressure wave is consistent with a clearance wave removing bolus residue from the oral cavity. Nicosia et al. (2000) described that most biphasic patterns achieved maximal peak on the initial peak followed by a smaller secondary peak after the bolus had exited the oral cavity. Again, this supports the concept of residual bolus clearance. These assumptions however, can only be tested with a concurrent visualisation of the bolus such as with videofluoroscopy.

The presence of an intermediate phase in certain individuals during water swallows reflects a differing ability to clear the bolus in a single movement. The proportion of those individuals generating biphasic swallowing patterns was found to increase with higher viscosity. Similar findings regarding increased multiple pressure peaks in viscous liquids were reported by Nicosia et al. (2000) and Steele et al. (2010). It is likely that this
was due to the increased difficulty in clearing a more viscous bolus from the oral cavity. Nicosia et al. (2000) also reported that multiple pressure peaks were observed more frequently in the elderly sample group than the younger sample. Therefore, in some individuals, the presence of an intermediate phase and resultant biphasic pattern could potentially indicate less efficient swallowing. As such, this observation could be a marker for increased susceptibility to oral phase dysphagia. Further research on this possibility is warranted.

The anterior 2/3 of the tongue is a bilateral structure where extrinsic muscles do not cross the midline. Hence the lateral margins have the ability for symmetric elevation or asymmetric rotation (Stone, 1990). Regarding the behaviour of the lateral margins, Miller and Watkin (1996) suggested that asymmetry in the lateral margins of the tongue was required to contain the bolus prior to a midline propulsive force. With this in mind, a plausible explanation for the asymmetrical twisting phenomenon observed in some individuals could be due to a compensatory correction. If the bolus deviates towards the anterior lower pressure side, an asymmetric posterior correction could potentially move the bolus back to the midline and, therefore, present the bolus to the pharynx in the midline.

During swallowing, with the lips sealed and the velopharyngeal sphincter closed, a sealed environment exists (Engelke et al., 2009). In this study, the pressure gradients formed within this environment were found to be highly individual. The effects of negative pressure on the bolus head and body have not been reported thus far in discrete swallows. Previous research by Kennedy et al. (2010) and Kieser et al. (2011) highlighted the complex interplay between positive and negative forces during the oral phase of swallowing. Accordingly, they theorised that bolus clearance was significantly more complicated than a simplistic positive pressure wave. In this study, prior to the command to swallow, the bolus was held by the subjects under a wide range of pressures from -30 to + 30 kPa. Negative pressures gradients were found most often in the preparatory and intermediate phases. These negative pressures appear to be closely related to bolus capture and positioning before and after the primary pressure wave. Whether these negative forces act to initiate caudal flow at the head of the bolus requires concurrent visualisation of the tongue, bolus and absolute intra-oral pressure. Regarding the propulsion of the tail of the
bolus during the primary pressure wave, it appears that this is entirely a positive pressure phenomenon.

An interesting finding in this study was the fact that some pressure profiles appeared to be inconsistent with posterior flow of the bolus (CL, DK, and JF). In these cases the rise in anterior to posterior primary pressure wave did not surpass the pressure of the region immediately posterior to it. As Shaker et al. (1988) observed, non-maximal tongue palatal contact still caused bolus flow. As the bolus is incompressible I was not able to tell if palatal positive pressure was due to lingual pressure on the bolus or direct lingual contact after the bolus has passed. In these cases it must be assumed that the increased caudal pressures were those of the bolus between the tongue and the palate prior to complete linguo-palatal contact. This contact effectively obliterates the midline groove forcing the bolus into the pharynx and has been described as a posterior piston-like motion (Dodds et al., 1990). Further study of these patients with videofluoroscopic analysis of lingual and bolus movement would give valuable insight to pressure flow dynamics and bolus flow.
6 Conclusion

This study suggests that there was a swallowing pattern common to all participants. This was visualised by overlaying multiple individual swallow profiles on the primary midpalatal pressure peak. This basic pattern was then able to be divided into 4 stages to assist subsequent analysis of the effects of bolus variables on the pressure profile; these were the preparatory stage, the primary propulsive stage, the variable intermediate stage and the terminal stage.

The preparatory stage was highly variable and was probably related to the process of bolus containment and manipulation prior to the primary propulsive stage. The primary pressure wave in turn, was highly concordant between individuals with respect to timing and polarity. Extrapolation from other concurrent videofluoroscopic studies (Shaker et al., 1988; Cook et al., 1989; Dantas et al., 1990; Taniguchi et al., 2008) suggests that this event is associated with propulsion of the bolus tail through the oral cavity. However, individual pressures generated were highly variable and once again did not lend themselves to an average comparison. The basic sequential pressure pattern of the primary propulsive phase was an anterior palatal rise followed closely by a highly coordinated lateral palatal pressure rise. The 5 regions examined all peaked with a tight temporal relationship and gave a reasonable indication of the lateral blades and tongue tip pressing against the palate prior to a midline initial positive pressure wave. The presence of an intermediate phase with its secondary sequential pressure waves most likely relate to incomplete clearance of the bolus.

The generic pressure profile provided a uniform descriptive pattern to describe and compare swallowing pressure patterns between individuals. Though a robust tool to describe basic coordination of timing and polarity of absolute pressure, it was not sufficiently accurate to describe the marked individual variety that was observed in this study. The development of several sub-classifications greatly improved the ability to describe pressure behaviour within and between individuals with respect to swallowing interventions. These were, tipper and dipper profiles in the preparatory phase; rollers and
slappers in the primary propulsive phase; and monophasic or biphasic depending on the presence of the intermediate phase.

It must be noted that the amplitude of pressures developed varied considerably between participants and these pressures could only be interpreted at an individual level. Despite the marked inter-individual differences in maximal, minimal, mean and RMS pressures generated throughout the swallow, the range between maximum and minimum between participants was less varied. This was found to be approximately 80 kPa with a standard deviation of 10 kPa.

The addition of a mild apple flavour to aid palatability had no significant effects on overall pressure profile or average duration. At the individual level, there were some minor changes in a several participants, 1 participant showed increased duration and 2 revealed reductions in maximal pressures generated.

The increase in bolus viscosity to a honey-thick level, as used in dysphagia management, had significant effects on average pressure profile and duration. The preparatory phase saw an increase in the proportion of individuals displaying dipper type swallows increase from 3 out of 10, to 7 out of 10. There was no difference in the primary propulsive phase noted. The proportion of those displaying an intermediate phase, resulting in a biphasic swallow, increased from 4 out of 10, to 7 out of 10. Finally, there was an increase in small clearance type swallow patterns noted in the terminal phase of 3 participants. There was a significant increase in the average swallow duration from 1.08 to 1.44 s with increased viscosity. However, the individual response varied from no change in 3 subjects, to more than doubling by 2 subjects. These increases in duration occurred primarily in the preparatory phase and to a lesser extent, the intermediate phase. Regarding changes in pressure, these were highly variable and showed no overall pattern. However, an individual trend towards an increase in posterior RMS was shown by 7 out of 10. All these changes suggest an increase in difficulty manipulating and clearing the bolus, rather than a change in the mechanics of the primary propulsive pressure wave.

An important finding of the present investigation was the marked asymmetry of lateral pressures. Though all subjects displayed symmetry in timing, coordination and polarity,
none displayed symmetrical pressures in all lateral channels. The anterior region showed greater bilateral symmetry with 6 out of 10 participants having relatively equivalent pressures. However, lateral pressure asymmetry was evident in all 10 participants at the posterior hard palate. The anterior symmetry displayed by 6 participants was consistent with an even containment of the bolus in the palatal midline prior to the midline propulsive wave. Interestingly, all 4 participants who displayed anterior asymmetry showed a preference to the right side, which was followed in all cases by a left sided posterior dominance. This twisting of lateral pressures was consistent with the bolus being squeezed back into the midline as it deviated to the low-pressure left side.

Negative pressures were involved primarily in the preparatory and intermediate phases of the swallow. They appeared to be related to manipulation of the bolus into the midline groove of the tongue, prior to the midline primary or secondary propulsive waves. There was no evidence of negative pressures developing posterior to the advancing primary pressure wave. This suggests that negative pressures are unlikely to contribute to the propulsion of the bolus. However, without concurrent visualisation of the tongue and bolus, speculation on bolus flow dynamics are based entirely on extrapolation from other studies that have compared positive pressure patterns with concurrent visualisation of the bolus and tongue.

The lack of concurrent visualisation of the tongue and bolus in this study left an important question unanswered. In the case of 3 subjects there appeared to be a pressure profile that was inconsistent with posterior bolus flow. In these subjects the anterior pressure at no time exceeded the pressure of the regions posterior to it in which case the bolus would be expected to remain in an anterior position. As bolus transit occurred successfully it is probable that the bolus was held in the sealed tube created by the anterior and lateral tongue margins, and the higher posterior pressures recorded were due to the incompressible bolus-head as the antero-posterior obliteration of this tube carried the bolus posteriorly.

The most significant finding of this research was the unique individuality of participants. This was evident not only in the manner in which the timing and polarity was altered by changing bolus variables, but also in the markedly different pressures generated at various
regions of the oral cavity. Within this young healthy sample, the temporally static pressure values such as maxima and minima were too variable to describe an average intra-oral pressure at any stage or region of the oral cavity. However, at an individual level they allowed grouping of individuals into high-, medium- and low-pressure swallowers.

In summary, these results suggest that though changes in pattern and pressure occur with altered bolus variables, these can only be assessed reliably at an individual level. The variable and sometimes unpredictable nature of individual responses to viscosity change in this study highlighted the importance of individual assessment with respect to dysphagia management. The major implication from this study is that where a group average existed, it was rarely universal and individual variation often led to widely disparate responses. As such, if we are to avoid increasing the risk of aspiration in the dysphagic population, it is imperative that management and response to changes is assessed at an individual level. Further study on dysphagic and aged populations is urgently required; however, this marked individuality seen at the young healthy level would be expected to persist in these more specialised population groups. Due to the unpredictable and marked variation within pressure ranges, patterns and regions, studies on swallowing pressures should be analysed with respect to individual results not a population average. Measurement of an individual’s overall pressure profile and swallowing pressures relative to maximal swallowing tongue pressure, could potentially give an indication of the efficiency and overall performance of the tongue during the oral phase of the swallow. Assessment of lateral pressure patterns could also allow a more complete assessment of an individual’s ability to manipulate and contain the bolus.
7 References


8 Appendices

8.1 Information sheet for participants

Tongue pressure dynamics

INFORMATION SHEET FOR
PARTICIPANTS

Thank you for showing an interest in this project. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate we thank you. If you decide not to take part there will be no disadvantage to you of any kind and we thank you for considering our request.

What is the aim of the project?

The aim of this project is to test the intra-oral pressure exerted by the tongue on the palate and teeth during swallowing, chewing and speaking.

What types of participants are being sought?

We are looking for individuals, who have a basic understanding of oral anatomy and function.

- Exclusion criteria are; poor oral health, malocclusion, no history of mouth breathing or dysphagia, incompetent lip seal, taking antihistamines or other medications that cause xerostomia.

What will participants be asked to do?

Should you agree to take part in this project, you will be asked to wear a custom made plate for about 45 minutes during which time we will ask you to get used to the plate for 15 minutes, drink some water and water thickened with commercial starch thickener. This will be done with, and without, a small plastic cylinder between your lips to break the anterior oral seal.
While you do this, we will be measuring tongue pressure from 7 sensors placed in the metal plate. We will then ask you to repeat the entire performance on 2 subsequent days.

The construction of the little plate will involve a standard dental impression, following which a technician will make a chrome cobalt metal plate to fit your mouth comfortably.

The entire procedure will be under dental supervision, in a surgery at the Faculty of Dentistry.

**Can participants change their mind and withdraw from the project?**

You may withdraw from participation in the project at any time and without any disadvantage to yourself of any kind.

**What data or information will be collected and what use will be made of it?**

We will be collecting pressure data over time, generated by your tongue while eating drinking and speaking. **No personal data whatsoever will be gathered.**

We are trying to see how tongue pressure varies in your mouth over time and with function. These data will then be used in a mathematical model (Finite element analysis) to see what the effects of the pressure are on jaw architecture. Results of this project may be published but any data included will in no way be linked to any specific participant.

You are most welcome to request a copy of the results of the project should you wish.

The data collected will be securely stored in such a way that only those mentioned above will be able to gain access to it. At the end of the project any personal information will be destroyed immediately except that, as required by the University's research policy, any raw data on which the results of the project depend will be retained in secure storage for 5 years, after which it will be destroyed.

**What if participants have any questions?**
If you have any questions about our project, either now or in the future, please feel free to contact either:-

Professor Jules KIESER

Department of Oral Sciences, Faculty of Dentistry, University of Otago
University of Otago extension 7070

Email  jules.kieser@stonebow.otago.ac.nz

Or

Dr. Guy FARLAND

Email  farlandlocum@hotmail.com

Ph 0211822886
8.2 Consent form for participants

Tongue pressure dynamics

CONSENT FORM FOR PARTICIPANTS

I have read the Information Sheet concerning this project and understand what it is about. All my questions have been answered to my satisfaction. I understand that I am free to request further information at any stage.

I know that:-

1. My participation in the project is entirely voluntary;

2. I am free to withdraw from the project at any time without any disadvantage;

3. Personal identifying information will be destroyed at the conclusion of the project but any raw data on which the results of the project depend will be retained in secure storage for 5 years, after which they will be destroyed;

4. There are no risks or discomfort from our study:

5. Each participant will receive a $30 book voucher;

6. The results of the project may be published and will be available in the University of Otago Library (Dunedin, New Zealand) but every attempt will be made to preserve my anonymity.

I agree to take part in this project.

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(Signature of participant)                                       (Date)

The University of Otago Human Ethics Committee has approved this study. If you have any concerns about the ethical conduct of the research you may contact the Committee through the
Human Ethics Committee Administrator (ph 03 479 8256). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.