THE THICKNESS OF PARIETAL BONES IN A NEW ZEALAND SAMPLE OF CADAVERIC SKULLS IN RELATION TO CALVARIAL BONE GRAFT, 2007-2011

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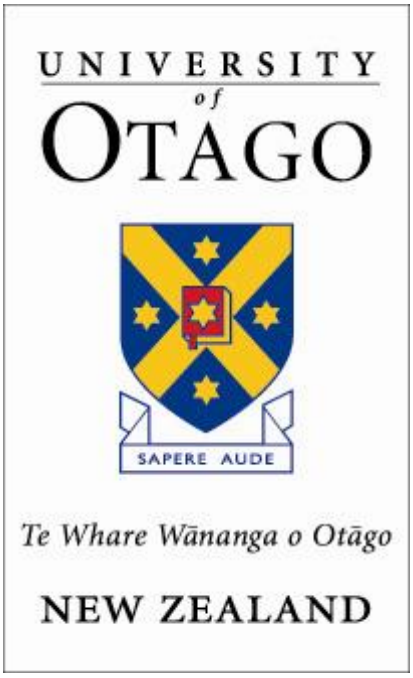

ABSTRACT

Objectives: (1) To evaluate the average thickness of the parietal bones in a New Zealand European sample of cadaveric skulls; (2) to construct a thickness map of the parietal bone; and (3) to identify the ideal site(s) for calvarial bone graft harvest using the parietal bone.

Study Design: Twenty-five wet cranial vaults (fifty parietal bones) of New Zealand European origin were obtained from the Department of Anatomy at the University of Otago, New Zealand.
A total number of 3887 points (average of 78 points per bone) in 135 equivalent locations throughout the specimens were measured for its thickness using an electronic calliper. Statistical analysis was performed using a software system R. Analyses to identify the ideal harvest sites were conducted so that they fit features of ideal harvest site described in the literature as: 6 mm of minimum thickness; and 2 cm way from the midline.

Results: The overall average thickness was 6.69 mm with a standard error of 0.22 mm. The average thickness at different locations ranged from 2.85 mm to 6.93 mm. The report also observed a progressive thickening of the parietal bone in both medial and posterior directions. A thickness map clearly demonstrated regions with varying thickness of the parietal bone in its different regions.
Of all 135 locations, a significant proportion - forty-seven locations (34.5%) - had an average thickness greater than 6 mm. The proportion was also high – twenty-seven locations (20%) - after excluding the locations within 2 cm from the midline. However, a frequency of encountering bone with an actual thickness less than 6 mm was also high at 20.6% in this region. The frequency was reduced to 13% in locations with an average thickness greater than 6.5 mm. However, only a very limited number of locations (3/135 = 2%) had an average thickness greater than 6.5 mm in our study sample after excluding the locations within 2 cm from the mid-sagittal plane.

Conclusions: Parietal bone thickness in our study sample is similar to that of other ethnicities reported in the literature.
The ideal calvarial bone graft sites that safely meet the recommendations were found to be scarce in this study.

Further research to validate or update the current recommendations for the ideal sites of calvarial bone harvest sites including pre-operative imaging modalities is recommended.

PREFACE

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BMP:	Bone morphogenetic protein
CSL:	Coronal suture line
CT:	Computed tomography
DFDBA:	Demineralised freeze-dried bone allograft
DBM:	Demineralised bone matrix
EGF:	Epithelial growth factor
HIV:	Human immunodeficiency virus
IGF:	Insulin-like growth factor
MDAF:	Macrophage-derived angiogenesis factor
MDGF:	Macrophage-derived growth factor
OMS:	Oral and maxillofacial surgery
PDGF:	Platelet derived growth factors
S.E.:	Standard error
SICG:	Split in situ calvarial graft
SOTG:	Split on table calvarial graft
SSL:	Sagittal suture line
TGF-β:	Transforming growth factor-beta

INTRODUCTION

Bone grafting in oral and maxillofacial surgery (OMS) has been used for many decades for the reconstruction of the craniofacial skeleton for congenital defects, trauma, post-tumour resection, and pre-prosthetic augmentation of the severely resorbed alveolus secondary to tooth loss.[1] There is also an increase in the number of procedures requiring bone grafting in conjunction with dental implant placement in general dentistry.[2]

There are several types of bone graft: autogenous graft (harvested from same individual who will receive the graft); allograft (derived from a member of same species as the host individual); xenograft (derived from a genetically different species); and alloplastic graft (synthetic material). Currently, the autogenous bone grafts are considered as the gold standard due to its proven efficacy with no risk of immunological rejection or potential transmission of infectious diseases.[2]

Autogenous bone grafts can be harvested from both extraoral (e.g. calvarium, iliac crest, ribs, tibia, etc.) and intraoral donor sites. Calvarial bone grafts have several advantages which include: proximity to the recipient site; possibility of sharing a same surgical field as the recipient site via coronal flap in certain situations; less resorption; scar well hidden in the hair bearing region; and less overall complication rate and morbidity.[3,4] Despite these advantages, harvesting the calvarial bone graft can cause intracranial complications such as iatrogenic damage to dura matter, cerebral cortex, and vital vascular structures namely the superior sagittal sinus and middle meningeal artery.[5] In order to minimise these potentially devastating complications, several studies have looked at the thickness of the parietal bone to determine the safest sites for harvesting the graft.

A small number of cadaveric studies have found variations in the thickness of bone within the same parietal bone. The mean thickness ranged from 4.73mm in its thinnest part to 7.72mm in its thickest part in these studies.[6,7,8] Jung et al[8] concluded that the optimum site for harvesting is from the posteromedial portion of the parietal bone where the bone is thickest. Other studies have proposed thickness maps as a practical guide to surgeons for choosing the ideal calvarial bone graft harvest sites.[6,7] Although the maps are excellent at identifying thick regions of the skull, they do not accurately reflect on the features of the ideal harvest sites

described in the literature which are minimum thickness of 6 mm and a minimum distance of 2 cm away from the mid-sagittal plane in order to prevent damage to the superior sagittal sinus.[5,9,10] However, these ideal features are purely anecdotal and lack any scientific evidences.

No information has been published on the thickness of the parietal bones in a New Zealand population. This report will determine the average thickness of the parietal bones in its different regions using the cadaveric cranial vaults using a New Zealand sample. Using this data, a thickness map may be developed to identify the optimal locations using anatomical landmarks. Finally, identifications of the ideal calvarial harvest sites will be performed using a minimum thickness of 6 mm and 2 cm away from the midline as a guide.

LITERATURE REVIEW

Definition of Bone Graft

The definition of bone graft can be confusing as many clinicians wrongly use the term bone graft, alloimplant or alloplastic implants, and free flap interchangeably. One definition of graft is a living tissue or organ containing donor cells that are designed to survive in the recipient bed.[11] Although it may hold true to some extent for autogenous bone grafting, this definition does not incorporate other types of bone graft where donor cells are either absent or nonviable. A more encompassing definition therefore would be the one described by Muschler & Lane[12] where, "a bone graft is any implanted material that, alone or in combination with other materials, promotes a bone healing response by providing osteogenic, osteoconductive, or osteoinductive activity to a local site".[11] The key aspect of the bone graft lies in its capacity to promote these healing responses whereas alloplastic implants (e.g. zygoma implant and temporomandibular joint implant) do not.[2] The definitions of each are as follow:

- Osteogenesis:
    - Formation of new bone from osteocompetent cells that survived in the graft.[13]
- Osteoinduction:
    - Formation of new bone from the differentiation of mesenchymal cells from the host stimulated by osteoinductive proteins such as bone morphogenetic proteins (BMP) and insulin-like growth factors 1 and 2 (IGF-1 and -2).[13]
- Osteoconduction: Formation of new bone by ingrowth of vascular tissue and mesenchymal cells from the host along a scaffold presented by the graft.[13]

The term vascularised bone graft may also be misleading as it is different from free bone grafts in that, not only the tissue itself, but the blood supply from the donor site is also transferred to the recipient site. A more appropriate description therefore would be a microvascular free flap. In comparison, a free bone graft solely relies on the blood supply from the recipient bed for its survival. For same reason, pedicled bone grafts should be termed as a pedicled bone flap.

Types of the Bone Graft

The most common way to classify the types of bone graft is from its source of origin. Furthermore, there are other ways to classify, or even sub-classify, the bone graft, according to its embryonic origin (endochondral vs. intramembranous), mineral content (cortical, cancellous, or combined), and preparation of the graft (e.g. block and particulate grafts).

Classification based on source

1. Autogenous bone graft:

An autogenous bone graft refers to a bone graft harvested from the individual who will also receive the graft. It has advantages of high efficacy, no immunogenicity, better patient acceptability, and is currently considered as the gold standard against which other types of graft are compared.[2] The disadvantages however include requiring a second surgical site with its associated morbidity and a longer surgical time.

The autogenous bone graft can be harvested in the form of cancellous, cortical, or cortico-cancellous grafts.[11] The cortical bone graft has a higher mechanical strength, but its high density and lack of diffusion capacity slows revascularization process and renders osteocytes nonviable.[13] Also, osteogenesis is impossible as the graft does not contain any osteoblasts or mesenchymal cells, hence, the graft only promotes osteoconduction and some degree of osteoinduction from the release of osteoinductive proteins (e.g. BMP, IGF-1 and -2) once the matrix resorbs.[11] In comparison, cancellous bone grafts have abundant osteoblasts and osteocompetent progenitor cells for osteogenesis and has a greater capacity for revascularisation due to its porosity.[10] The main disadvantage is lower mechanical strength. The cortico-cancellous graft has properties of both cortical and cancellous graft and is the most common choice of autogenous bone graft in OMS.

Cortical and corticocancellous bone grafts can be delivered in a block or particulate (small particles of bone) form whereas cancellous bone grafts are almost always delivered in a particulate form.[14] The block grafts have an advantage of being able to withstand early mechanical loading. Depending on the size of a graft, fixation using a reconstruction plate, miniplate, or lag screw/lag screw technique is required for this form of graft.[14] In contrast, the

particulate grafts require a containment system such as titanium mesh or membranes to keep the graft material at the site and to prevent soft tissue ingrowth.[14] Advantages of the particulate grafts are early revascularisation, good remodelling, and being able to be packed into small bony defects.[10,14] When used in sinus augmentation procedure, Sbordone et al[15] reported a significantly less volume reduction for iliac crest particulate graft (6.2%) compared to iliac crest block graft (16.7%). No statistically significant difference was seen with the iliac crest particulate graft and symphyseal block graft (2.1%).[15] The study however did not account for the early resorption of the grafts as the volume reduction was calculated based on the difference in bone height from pre-implant CT scan (3-6 months after the sinus augmentation) and CT scan one year after the implant placement.

Autogenous bone grafting may also be classified on the basis of its embryonic origin. Intramembranous bone refers to bone formation by direct ossification of mesenchymal tissue without cartilage. Endochondral bone formation arises from a preformed cartilaginous framework. Calvarium, facial skeleton, clavicle, maxilla and mandible are the only intramembranous bones in human skeleton. Studies have shown that intramembranous bone grafts undergo less resorption than endochondral bone graft.[4,16,17] Although the exact mechanism is uncertain, animal studies have postulated rapid vascularization and/or favourable microarchitecture of having thick bony struts in diploeic space as potential explanation.[4,16] A reported volume reduction for calvarial bone graft is 16.2% (after 6 months) and 19.2% (after one year) compared to 49.5% of volume reduction for iliac crest graft after six months when used as an onlay graft for alveolar ridge augmentation.[17,18]

2. Allograft:

The term allograft (homograft) refers to a graft harvested from a member of same species as the host individual. In order to minimize antigenic properties and to reduce host rejection, the graft material undergoes various processing steps, the degree and nature of this processing determines the classification of the allograft: fresh-frozen; freeze-dried; demineralised freeze-dried bone allograft (DFDBA); and demineralised bone matrix (DBM).[2] In general, fresh-frozen allograft is not used due to its risk of transmission of viral diseases including HIV.[2] Freeze-dried allograft are less immunogenic having had moisture removed but has downside of being only osteoconductive having had all cells killed in processing as well as not being able to release osteoinductive proteins hidden in bone minerals.[2] In comparison,

demineralised bone such as DFDBA and DBM are capable of releasing bone-inductive proteins hence has a good osteoinduction property.[2] However, these grafts lack mechanical strength and DBM in particular has a poor handling property due to its low viscosity. Recent advancement in combining copolymers to DBM may improve the handling property by making the mixture more viscous at the surgical site.[2,19]

3. Xenograft:

Xenografts (heterografts) are derived using sources from different species. The most commonly used xenograft in OMS is Bio-Oss (Osteohealth, Shirley, NY) derived from bovine bone. The bovine bone is deproteinated, particulated, and contained in a porous scaffold which makes it a good osteoconductive agent.[2] Another common xenograft is derived from coral.[2]

4. Alloplastic/synthetic materials:

Alloplastic bone graft refers to a synthetic material that has potential for osteoconduction and/or osteoinduction. There are many available types of synthetic materials available which are ceramics (hydroxyapatite, bioactive glasses, tricalcium phosphate, calcium sulphate), bioactive polypeptieds (e.g PepGen P-15), and synthetic osteoinductive growth factors (e.g recombinant human BMP).[1,2,11]

<u>Other classifications</u>

The future of bone grafting will likely use more of bone graft substitutes that would overcome the limitations of autogenous bone grafts and allografts.[20] Laurencin et al,[21] in 2006, proposed a classification system for the bone graft substitute materials (listed below).[21]

- Allograft-based bone graft substitutes:
    - DFDBA and DBM
    - DBM is currently available on its own or in combination with calcium sulphate or polymers on the market
- Factor-based bone graft substitutes:

    - BMP and other growth factors such as IGF -1 and -2, transforming growth factor-beta (TGF-β), platelet derived growth factors (PDGF), and recombinant human BMP
- Ceramic-based bone graft substitutes:
    - These are same as the ceramic materials described in the 'alloplastic/synthetic materials' section
- Polymer-based bone graft substitutes:
    - Various natural and synthetic polymers which promote osteoconduction
- Cell-based bone graft substitutes:
    - Stimulation of undifferenciated mesenchymal cells to develop into osteoblasts.

Bone Graft Healing

Bone grafts heal by regeneration rather than repair. As described previously, the hallmark features being one or more of the combination of osteogenesis, osteoinduction and osteoconduction.

The factors that determine adequate healing are: (1) graft factors such as type of graft, cell survival, pore size, amount of osteoinductive material within the graft that can be released; (2) host factors such as vascularity, number of osteocompetent cells and endothelial cells, oxygen tension that can all be affected in smokers, immunocompromised patients, and patient who received radiotherapy; and finally by (3) stability of the graft determined by type of graft, nature of defect, and use of fixation or barriers.[2]

The classical description of bone graft healing is described in two phases by Axhausen.[22] The first phase consists of survival of endosteal osteoblasts and mesenchymal cells within the graft that produce loosely organised osteoid bone. This happens over the course of a few weeks. The second phase then involves revascularisation of the graft and formation of more organised lamellar bone by host cells.[10] However, this biphasic process only explains the healing of the bone graft that has osteogenic potential (i.e. cancellous graft and cortico-cancellous graft).

Bone graft healing also appears to be in keeping with the principles of fracture healing (haematoma formation, granulation tissue formation, provisional callus, definitive callus, and

remodelling). Similarly, Bauer & Muschler[11] described sequence of biological events of bone graft healing as: (1) haematoma formation; (2) inflammation, migration, and proliferation of mesenchymal cells and development of fibrovascular tissue; (3) revascularisation; (4) osteoclastic resorption; (5) bone formation.[11]

Healing of cancellous bone grafts

The initial process of cancellous bone graft healing involves the survival of osteocompetent cells (endosteal osteoblasts and mesenchymal cells) within the graft. An inherent hypoxic (oxygen tension = 3 to 10 mmHg) and acidotic (pH = 4.0 to 6.0) environment at the recipient site is unfavourable for cells' survival as they rely on local diffusion of oxygen and nutrients until revascularisation takes place.[23] The surviving cells later will contribute to osteogenesis.

As soon as a graft is in place, haematoma formation and inflammatory process is initiated. Platelets in the haematoma degranulate and release several growth factors such as platelet-derived growth factors (PDGF), transforming growth factor-β1 and 2 (TGF-β1, TGF β2), epithelial growth factor (EGF).[13] These growth factors, together with inflammatory cytokines will attract and induce proliferation of host endothelial cells and osteocompetent cells. These host cells migrate along the scaffold provided by the graft and initiate the process of osteoconduction.

After one week, macrophages take over from platelets. Marx[23] proposed that an oxygen gradient of greater than 20 mmHg (recipient site = 3 to 10 mmHg vs. normal tissue = 50 to 55 mmHg) plays an important role at stimulating chemotaxis of the macrophages.[23] The macrophages secrete macrophage-derived growth factor (MDGF) and macrophage-derived angiogenesis factor (MDAF) for further angiogenesis and attraction of osteocompetent cells.

The revascularisation begins after two weeks and, at the same time, both donor and host osteoblasts start to produce and secrete osteoid materials. This process lasts for approximately six to eight weeks and, until this point, may be considered as the first phase in cancellous bone graft healing. The second phase starts when osteoclasts resorb the bone matrix resulting in the release of osteoinductive proteins (i.e. BMP, IGF-1 and 2). Once released, these proteins induce the differentiation of mesenchymal cells into osteoblasts, which in turn promotes osteoinduction. These osteoblasts will produce lamellar bone which ultimately

replaces the osteoid. This new bone develops into mature harvesian systems and finally remodels in response to mechanical demands placed on it. The graft will be 90% mature by 6 months.[10,11,13,23]

Healing of cortical bone grafts

The healing of cortical bone graft differs markedly from cancellous bone grafts. Osteocytes cannot survive transplantation due to insufficient diffusion owing to dense nature of cortical bone. The cortical density addition to a low surface area also slows revascularisation process. Furthermore, osteogenesis is not possible as osteocompetent cells are not present. Therefore, the first phase of bone graft healing is omitted. Another difference is that osteoclastic activity is initiated prior to osteoblastic activity in cortical bone healing, a process known as creeping substitution. In other words, the harvesian system is resorbed first followed by deposition of osteoid bone from host osteoblasts. Then, the second phase follows in similar manner to that of cancellous bone graft healing.[10,11,13]

Healing of cortico-cancellous grafts

Not surprisingly, the healing of cortico-cancellous bone grafts encompass aspects from both cortical and cancellous bone healing depending on the amount of cancellous portion within the graft. This type of bone graft is by far the most preferred bone graft in most OMS cases due to its osteogenic potential and mechanical strength.

The Use of Bone Grafts in OMS

There are a number of indications for the use of bone grafting in OMS. Bone grafting may be used in the treatment of congenital craniofacial deformities such as alveolar clefts and other anomalies such as Treacher Collins, Crouzon, and Apert's syndrome.[24,25] It is also used in reconstruction of defects resulting from trauma and from tumour resection.[1] Orthognathic surgery is another indication where an interpositional bone graft may be used to stabilize the osteotomy site, for example an inferiorly repositioned Le Fort I maxillary osteotomy.[9] Before the era of dental implants, bone grafting was commonly used in pre-prosthetic surgery to increase the height and/or width of severely resorbed edentulous ridge. The advent of dental implant surgery has opened up a huge range of new avenues for bone graft use in OMS which

include socket preservation, maxillary sinus augmentation via a lateral approach, filling defects such as dehiscence and fenestrations, and in some situations in guided bone regeneration.[2,26,27]

In OMS, each type of bone graft can either be used alone or in combinations. Commonly, xenograft and alloplastic materials are mixed with autogenous graft materials. When combined, two main advantages can be gained. Firstly, the amount of autogenous bone needed during harvesting is less, therefore reducing complications and morbidity associated with a minimized second surgical site. This may also influence the decision to consider an intraoral harvesting site rather than an extraoral one. Secondly, the synergistic effect of osteogenesis, osteoinduction, and osteoconduction is possible that might be absent or insufficient when the graft materials are used separately.

Autogenous bone grafts can be harvested from multiple donor sites, largely divided into extraoral and intraoral locations. Selection of the donor site is determined by size of the defect, amount of bone required, and location of host site.
Intraoral sites have advantage in that it is easily accessible and the harvest site may be incorporated into the same surgical field as the recipient site.[10] However, limitations include a smaller total volume and paucity of cancellous bone.[10]

The most common intraoral sites are the mandibular symphysis and the ramus of the posterior mandible. According to Toscano et al,[27] the mandibular symphysis and ramus provide 5-10 ml^3 and 5 ml^3 of graft volume respectively. Apart from ease of access, the mandibular symphysis yields cortico-cancellous bone as opposed to pure cortical bone when harvested from the ramus.[27] However, a higher complication rate is associated with symphyseal bone grafting with reported incidence of 43% of patients experiencing temporary paraesthesia of the chin post-operatively.[28] Lower lip ptosis, lip incompetence, and wound dehiscence have also been reported.[27] In comparison, reported complication rates associated with ramus grafts such as damage to the inferior alveolar nerve or lingual nerve, and fracture of the mandible are very low, study having observed no complications in fifty block grafts harvested from the ramus.[29] Damage to the long buccal nerve is more common but is less discernable to patients and therefore result in minimal functional deficit.[27] The harvesting of a ramus graft is contraindicated in cases of: distance less than 10 mm from the superior aspect of the inferior alveolar canal to the external oblique ridge; presence of pathology associated with an

imparted third molar (e.g. pericoronitis); and previous history of mandibular sagittal osteotomy.[30] Presence of an impacted lower wisdom tooth and a narrow space between the most distal tooth and the coronoid process may also make the procedure difficult. Other intraoral donor sites include bone collected from the dental implant preparation site, the outer cortex of the mandible and maxilla, the coronoid process, the maxillary tuberosity, the zygomatic buttress.[10] These alternative sites provide comparatively very small amounts of bone graft material but in selected cases may be enough to be useful.

Many surgeons prefer the use of the anterior iliac crest as an extraoral donor site as it provides greater graft volume and has the highest cancellous bone content. [10] According to Wilk,[10] up to 50 ml^3 and 90 ml^3 of graft volume can be harvested from the anterior and posterior iliac crest respectively. However, a higher surgical morbidity is associated with iliac crest bone graft harvesting with complication rates of up to 25%. Reported complications are haematoma, seroma, neurovascular injuries, gait disturbances, fracture of the iliac wing, and peritoneal perforations.[10]. Other disadvantages include increased resorption of the graft, greater distance between donor and recipient sites necessitating separate surgical fields to differentiate between "sterile" and "clean" areas, and a longer hospital stay.[10,17] Other extraoral donor sites are costochondral graft, tibia, and calvarium.[10]

Calvarial Bone Graft

Background

Muller[31] and Konig[32] in 1890 independently described the use of calvarial osteocutaneous flap to reconstruct cranial defects. Later, these authors used calvarial bone chips for same purpose.[31,32] The first description of split thickness calvarial graft was made by Lecene[33] in 1920. More recently, in 1982, Tessier[24] extensively described the use of calvarial graft in 103 patients with 234 calvarial grafts to reconstruct both cranial and midfacial defects secondary to trauma or congenital deformities.

Harvesting bone from the calvarium has several advantages over other bone graft donor sites. It is a membranous bone which is known to undergo less resorption compared to other extraoral donor bones of endochondral origin.[4,16,17] Another significant advantage is the low complication rates, reported to be between 0.18% to 5%.[5,24] Other advantages include:

accessibility; possibility of sharing same access as recipient site in some situations; inconspicuous scar hidden in hair bearing region; no limitations in ambulation; shorter in-patient hospital stay, and less postoperative pain.[24,34,35] The major disadvantages of the calvarial bone graft include less graft volume than iliac crest, less amount of cancellous bone, less malleability, visible scar in bald patients, contour irregularities of the donor site, and potential injury to the incracranial contents.[35] Concurrent activity using two surgical teams (as for harvesting iliac crest bone) is also not possible due to space limitation,

The uses of calvarial bone grafts in OMS is diverse but mainly reconstruction of fractures involving the orbital wall/floor and nose; midfacial reconstruction following tumour resection; alveolar augmentation; maxillary sinus augmentation; grafting of alveolar clefts; and cosmetic rhinoplasty have been reported.[24,26,35-38]

Calvarial bone graft harvesting technique

The recommended site for calvarial bone graft harvesting is on the parietal bone on the non-dominant hemisphere, 2cm away from the sagittal midline, and as posteromedially as possible.[10] The parietal bone consists of three different layers: the outer table, the inner table, and the diploeic space (cancellous equivalent), and the calvarial bone graft can be obtained from one or more combinations of these layers (Figure 1).

Access to the bone may be achieved using a full thickness incision locally over the area or in conjunction with a full coronal flap incision, incorporating the harvesting of the bone graft into surgical access for other areas of the craniofacial skeleton. Dissection is carried through the subgaleal plane until adequate exposure is gained followed by an incision through the pericranium in order to elevate a periosteal flap that is approximately 1 cm wider than the limits of the desired graft size.[10,39]

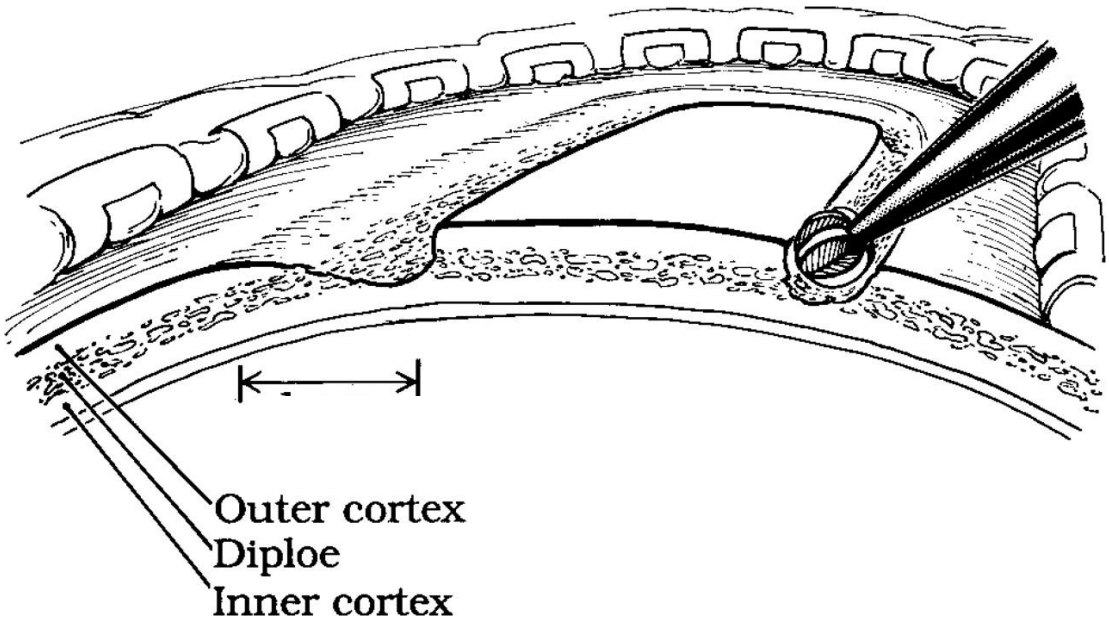

Figure 1. Coronal section through the calvarium illustrating the layers of the parietal bone[40]

Once exposure is obtained, Tessier[41] describes four classical ways to obtain the calvarial graft: (1) split on table calvarial graft (SOTG), (2) split in situ calvarial graft (SICG), (3) chips taken with a hand-held brace, (3) chips generated by the hand-powered osteomicrotome. More recently, a similar description was made by Strong & Moulthrop[35] who classified it into: (1) bone paté; (2) bone curls or chips; (3) outer table graft; (4) full thickness graft. Wilke[17] simply describes outer and inner table grafts. To combine all of them together, calvarial bone grafts can be harvested as bone paté, bone chips, outer table, inner table, or in full thickness.

Bone paté refers to shaving off layers of bone from the outer table with a cutting bur which is then collected in a suction trap.[35]

Bone chips are obtained from both outer cortex and the diploeic space with an osteotome after making a 'bony island' with a bur with the graft material particulated to from small chips of bone.[35]

An Outer table graft is the same as SICG. In this technique, a 'bony island' is created initially with a bur outlining the desired size of the graft. The cut extends just into the diploeic space. Wilke[10] then recommends bevelling of one or more sides depending on the size of the graft.

This bevelling allows the introduction of a curved osteotome into the diploeic space parallel to the surface of the outer table.[10] Once inserted, the osteotome is gently tapped until separation occurs. The use of a Gigli saw, oscillating saw, and more recently, piezoelectric devices have also been reported for this purpose.[35,41,42]

For an inner table and full thickness graft, a formal craniotomy is required. In both cases, the dura needs to be resuspended after the graft is taken. For an inner table graft, the outer table is separated and returned to defect site for coverage and fixation.[10] For a full thickness graft, Tessier[41] recommends covering of the defect with bone chips.

Complications of calvarial bone graft

As discussed previously, the overall complication rate of calvarial donor site is low.[5,28] When they do occur, complications are usually localised and minor in nature. These include local wound infection, haematoma, and seroma.[3,5,43] Major complications may occur from time to time. A survey of forty-two surgeons (mainly the members of the International Society of Craniofacial Surgeons) who performed 12,673 calvarial grafts reported a small number of damage to the dura, middle meningeal artery, superior sagittal sinus, brain tissue, and eight postoperative neurological disturbances (four permanent and four temporary).[5] Other complications such as intracranial haematoma, intracranial infections (meningitis and encephalitis), and cerebrospinal fluid leaks are also possible.[3] Inadvertent dural exposure is reported to be 11%.[5] The dural exposure is not generally considered as a complication as it does not cause any negative consequences on its own. Not surprisingly, these detrimental intracranial complications are of great concern to both surgeons and patients and for this reason several studies have looked at the thickness of calvarial graft in order to identify the safest sites for harvesting the graft.

Calvarial bone thickness and ideal harvest site

Historically, it has been shown that the human skull bone is highly variable in its thickness both between individuals and within the individual themselves.[44] Parietal bone is also found to be the thickest bone of the human cranial vault, hence it is the preferred site for the calvarial bone graft harvest.

Pensler & McCarthy[45] directly measured the thickness of the skull using two hundred cadaveric specimens with a micrometer.[45] The measurements were performed at six different locations (two on the frontal bone and two on each parietal bone) on the skull. In the study, the absolute thickness was found to vary between 3 mm to 12 mm with the mean thickness ranging from 6.8 mm to 7.72 mm. The authors also noted a consistent and gradual thickening of the bone as the measurements preceded posteriorly.[45]

Hwang et al[7] constructed a thickness map based on Korean population. The authors measured thickness of the parietal bone in fifteen different points using forty-four skulls. The study reported the thickest part of the parietal bone to be at the posteromedial region near the lambda with an average thickness of 6.67 mm. The thinnest part was near the pterion with an average thickness of 4.73 mm. With their data, the authors constructed a thickness map of the parietal bones that may be able to serve as a practical guide for surgeons.[7] Moreira-Gonzalez et al[6] also created a similar map with similar results using Caucasian and African American skulls. Although the regional variations in the map were similar in these two studies, the skulls in the latter study had an average thickness ranging from 5.3 mm to 7.5 which is considerably thicker than those of Korean skulls.[6] Both maps are excellent at guiding surgeons at locating the areas with greater thickness. However, strictly speaking, the maps do not reflect on the features of the ideal calvarial bone graft sites described in the literature as a minimum thickness of 6 mm and 2 cm away from the sagittal midline.[5,9,10] In regards to the former, the maps are excellent at showing the regions with an average thickness greater than 6 mm. However, what they do not show is the chance of encountering bones with an actual thickness less than 6 mm in that region. Such chance or risk would be of more value to surgeons. In regards to the latter, the maps have no scales or anatomical landmarks to determine the distance of a particular region from the sagittal midline.

Other authors place more importance of the minimum thickness of 2 mm of the dipoleic space as the layer represents a safe cleavage plane.[46] Jung et al[8] conducted a study measuring thickness of different layers of the parietal bone in forty-seven Korean skulls. The total thickness of the parietal bone ranged from 5.04 mm to 7.17 mm. It was also consistent with other studies in that the thickest region was situated at the most posteromedial region. The inner plate was also found to be thickest at the most posteromedial area. In contrast, the outer plate was noted to be thickest at the anteromedial region.[8] However, it is disappointing that the study did not analyse and reported on the thickness of the diploeic layer although it

appeared that the layer was thickest in the posteromedial region with thickness exceeding 2mm in all regions studied according to author's calculation using their data.

A few studies looked at the variables that may affect the thickness of the skull. Moreira-Gonzalez et al[6] have found that African American skulls were significantly thicker than those of Caucasians, 6.61 mm and 6.03 mm respectively. The authors also found that the skulls were thicker in females. For the age-related changes, Maves & Matt[46] reported that the human skull reaches 75 to 80% of its thickness by the age of five and reaches the overall size of an adult by the age of eight.[46] Thereafter, slow growth further occurs until the age of 20.[8] Moreira-Gonzales et al[6] have found no significant difference in total thickness of the parietal bone according to the age. However, Sullivan and colleagues[47] reported on age related thinning of the total thickness owing to progressive thinning of the inner plate.

A few studies have revealed the use of preoperative imaging to predict the ideal harvest site. Koenig et al[9] used CT scans in ninety-six patients from new born to twenty-one years of age. The study found that the CT scan was accurate to +/- 5%. However, only five patients out of ninety-six patients underwent surgery to verify the accuracy.[9] The study also failed to address difficulties in translating information from 2-dimensional CT scan to actual patients. Elahi et al[3] reported on the use of preoperative ultrasound to predict the thickness of the parietal bone. Ten adult cadaveric skulls were used in the comparison between ultrasound measurements to actual physical measurements using callipers. The results showed a good correlation between the two and authors concluded that ultrasound could have significant implications in guiding the harvest of outer table graft.[3] However, no clinical follow up trial has been published.

As mentioned above, the ideal features of calvarial bone graft harvest site described in the literature are: the minimum total thickness of 6 mm; 2 cm away from the sagittal midline; and the minimum thickness of 2 mm of the diploeic space. These ideal features, however, seem purely anecdotal and lack any scientific evidences. The recommendation of the '2 cm away from the sagittal midline' was based on a theory that it would reduce the risk of damaging the superior sagittal sinus. The superior sagittal sinus runs along a groove in the mid-sagittal line on the inner surface of the skull. A mean width of the vessel has been found to be 4.3 mm,[48] which makes the safe distance of 2 cm somewhat peculiar. Likewise, the 'minimum thickness of 2 mm of the diploeic space' to allow for a safe cleavage plane and the 'minimum total

thickness of 6 mm’ to prevent damage to the intracranial structures only hold theoretical values without any scientific proof.

Aims

1. To evaluate the average thickness and regional variations in thickness of the parietal bones in a sample of cadaveric skulls from New Zealand Europeans.

2. To construct a parietal bone thickness map.

3. To identify the ideal sites for calvarial bone graft harvest using the parietal bone.

Materials and Methods

Sample

Twenty-five wet cadaveric cranial vaults (fifty parietal bones) were obtained from the Department of Anatomy at the University of Otago, Dunedin, New Zealand. The bodies were bequeathed to the Department under the Human Tissue Acts (1964, 2008) of which twenty-five cranial vaults were available for use in this particular research.

This study followed the ethical and clinical guidelines of the Department of Anatomy and full approval was gained with a condition that no structural damage will be made to the specimens.

Background data collection

Background information such as gender, age at death, and cause of death were obtained, however, the Department of Anatomy could not provide any further details on past medical history such as bone related disorders.

Measurements of the parietal bone thickness

Pencil markings were made on the cranial vaults to determine the points where measurements were to be taken. Each cranial vault was identified for its anatomical landmarks (coronal suture, sagittal suture, superior temporal line, and lambdoid suture). Several lines were drawn (Figure 2 and 3), following an adapted design used in Jung's study.[8] Firstly, lines of best fit were drawn along the sagittal and coronal sutures (termed as SSL and CSL respectively). Secondly multiple lines parallel to the SSL and CSL were drawn with a 1 cm gap in between. These lines were then termed as S lines and C lines. A manual calliper was used for this purpose. The S lines were further named as S1, S2, S3 and so forth progressing from the SSL towards the inferior temporal line. The C lines were named as C1, C2, C3 and so forth progressing for the CSL towards the lambdoid suture. The right and left parietal bone was done separately.

The, thickness measurements were undertaken at the bisecting points of S and C lines. These were labelled as S1C1, S1C2, and so on. There were a total number of 3887 bisecting (average of 78 points per bone) points in 135 equivalent locations throughout the specimens. A measuring device used for this purpose was an electronic calliper (Warrior digital calliper, accuracy = 0.01 mm) which was modified to fit the curvature of the cranial vaults (Figure 4). The measurements were carried out by one examiner and recorded on a Microsoft Excel Spreadsheet. The recordings were re-checked by one person (other than the examiner) for accuracy. A total number of three measurements per point were performed and the measurement with the minimum thickness was taken as a final value. No sites beyond the inferior temporal lines were measured as residual muscle attachment would create inaccuracy. Also, no measurements beyond the lambdoid suture were carried out.

Statistical analysis

Statistical analyses were performed using the software system R (Vienna, Austria).[49]

For the thickness of the parietal bone, a linear mixed model approach was used to estimate the overall average thickness, average thickness among different gender and side, and average thickness in different locations. The linear mixed model approach was chosen in order to account for the multiple measurements collected from the same specimen (i.e. correlated data). Furthermore, a univariate mixed model analysis was conducted to evaluate any statistical associations between the variables (gender and side) and thickness.

To evaluate regional variations in thickness, three main analyses were performed. Firstly, a thickness map was produced based on the average thickness among different locations. Secondly, a multivariate analysis was performed to determine the difference in thickness among each location. Finally, using a linear mixed model, an average thickness for each line (S lines and C lines) was estimated to assess for any variations in a mediolateral (S1 to S9) and anteroposterior (C1 to C9) direction. This analysis was carried out by fitting a linear model to different thickness among different lines. A p-value (<0.05) was used to evaluate statistical significance and R^2 was used to predict the accuracy of the linear relationship.

Analyses to identify the ideal sites for calvarial bone graft harvest were performed using features of 6 mm of minimum thickness and 2 cm away from the midline as a guide. Firstly,

all the locations with an average thickness greater than 6 mm were identified and calculated in proportion. Secondly, the first step was repeated after excluding the locations within 2 cm from the midline (i.e. excluding locations along the S1 and S2 lines). Thirdly, frequencies of encountering a bone with an actual thickness of less than 6 mm in locations with an average thickness greater than 6 mm were calculated. Lastly, to assess for any improvement, the same steps were repeated with locations with an average thickness greater than 6.5 mm.

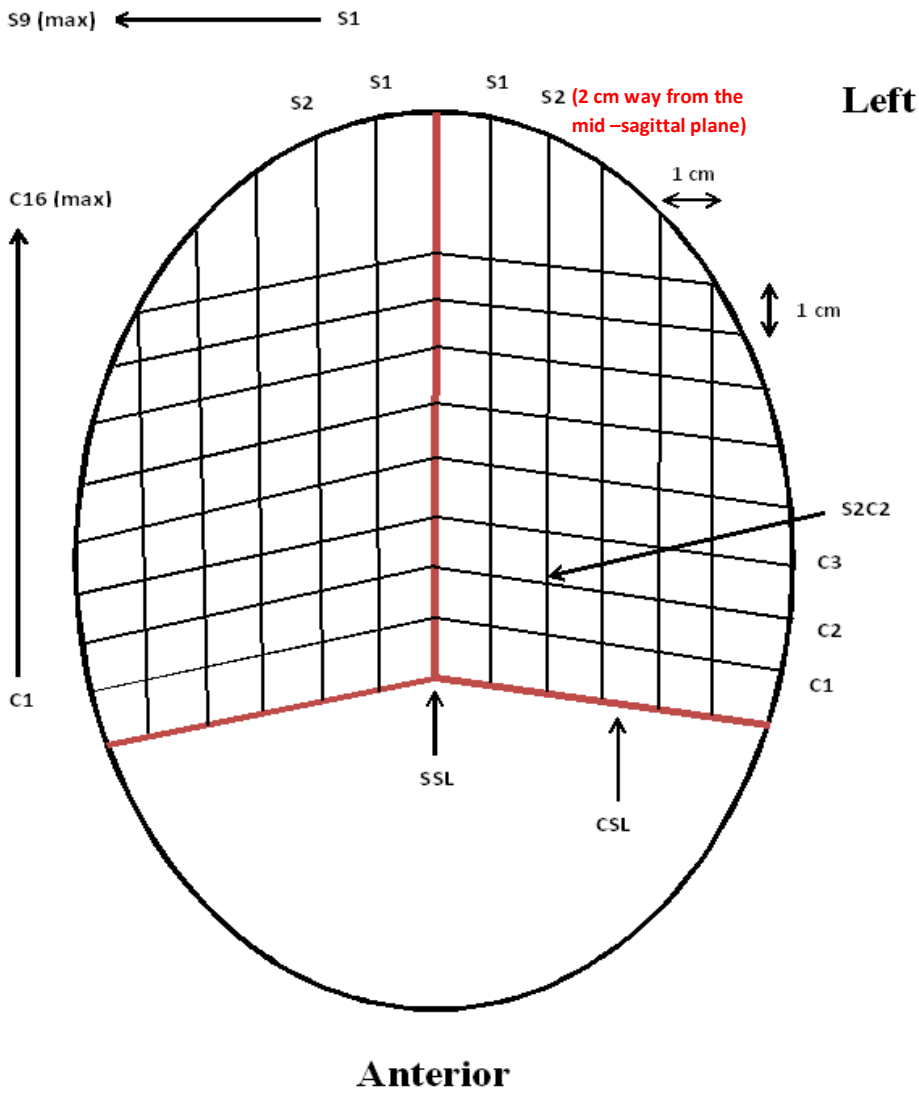

Figure 2. Schematic diagram illustrating lines and points on the cranial vault.

SSL = line of best fit along the sagittal suture; CSL = line of best fit along the coronal suture; S1 = line parallel and closest to SSL, S2 = Second parallel line to SSL, C1 = line parallel and closest to CSL, C2= Second parallel line to CSL, gap between the lines = 1, arrow indicates S2C2 point as an example.

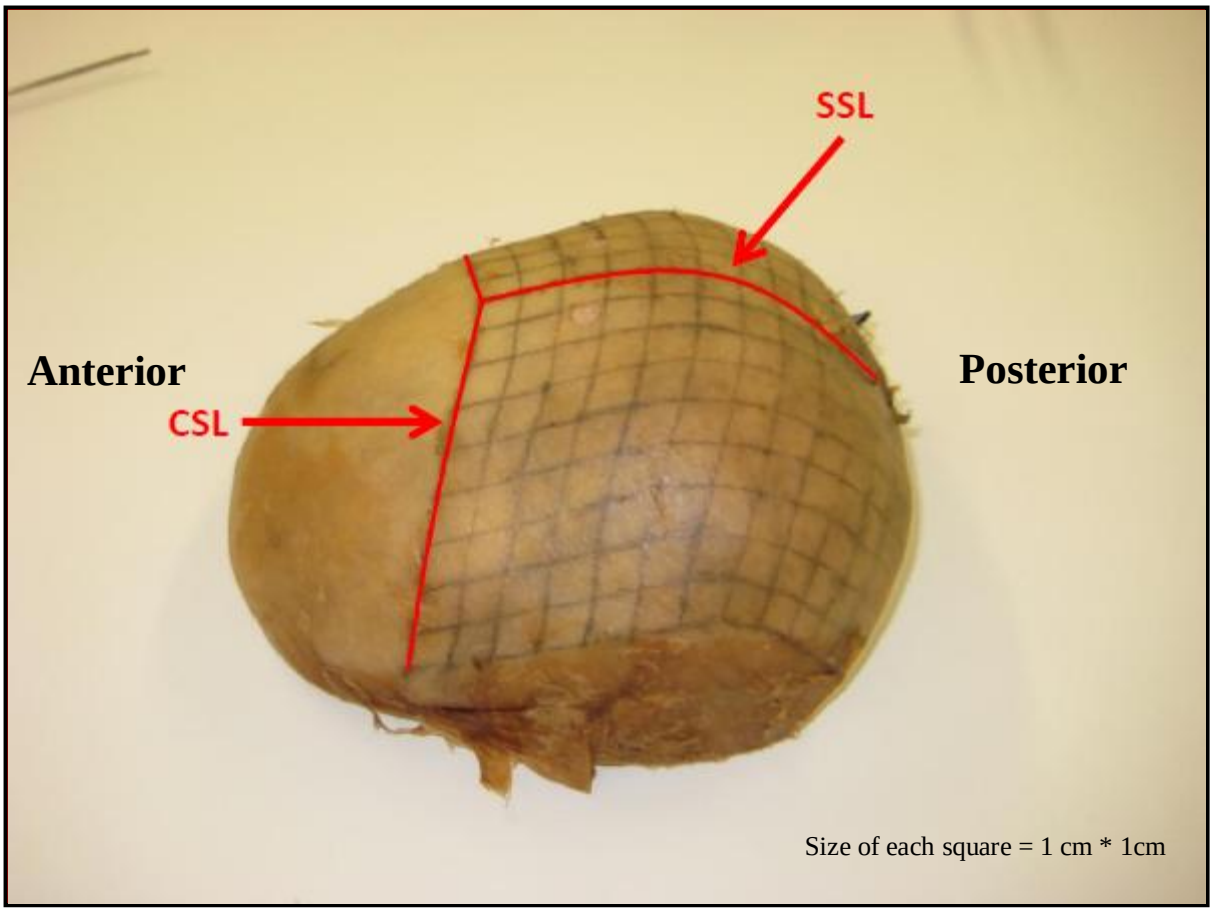

Figure 3. Photograph of a cranial vault showing lines drawn on a cranial vault. Arrows pointing at SSL and CSL.

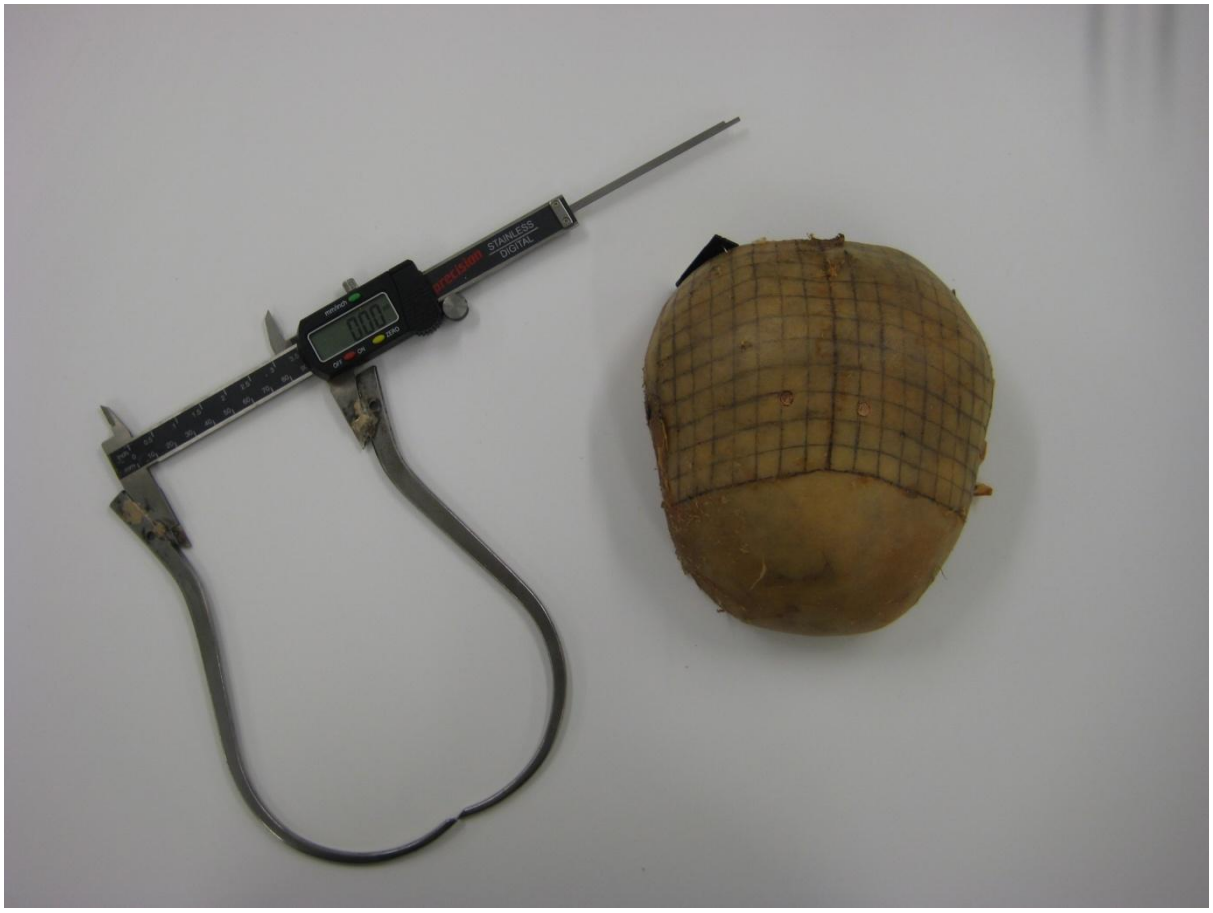

Figure 4. Modified electronic calliper and a cranial vault with lines

Results

Demographics

Of the total of twenty-five cranial vaults, the age at death were identified in twenty-two individuals. The average age at death was eighty years. The gender was identified in twenty-three specimens of which twelve were female and eleven male (Table 1).

Thickness of the parietal bone

The overall average thickness of the points using a correlated data was 6.69 mm with a standard error of 0.22 mm. The average thickness among different locations ranged from 2.85 mm to 6.93 mm.

The actual thickness ranged from 2.55 mm to 13.1 mm. Of the total of 3887 points 1997 points (50%) had thickness greater than 6 mm.

The gender and sex variables were found not to have any statistically significant association with the thickness (Table 2).

Regional variations in parietal bone thickness

There was a trend for progressive declination in thickness from the S1 line towards the S9 line in a linear relationship. The expected decrease in thickness for each consecutive line was 0.2 mm. This was statistically significant with a p-value of 0.0003. The linear relationship had a high goodness of fit with R^2 of 0.83 (Figure 5).

Conversely, a trend for progressive inclination in thickness from the C1 line (6.75 mm) towards the C16 line (7.93 mm) was observed. The expected increase in thickness was noted to be 0.07 mm for each consecutive line which was statistically significant with a p-value of 0.0005. However, as apparent in the scatterplot graph, the plots are more randomly distributed giving it a poor goodness of fit for the linear relationship with R^2 of 0.56 (Figure 6).

The thickness map clearly shows a regional variation in thickness of the parietal bone demarcated well with borders and in different colours (Figure 7). A region with an average thickness greater than 6 mm is demarcated by a U-shaped outline (bottom of the U facing lateral direction), covering a relatively large area between S1-S5 and C6-C11. A smaller U-shaped outline (bottom of the U is narrower and faces lateral direction) borders the area with an average thickness greater than 6.5 mm, located mainly along the S1 line in mid to posterior part of the parietal bone. Of note, the parietal bone is thin at the most posterior aspect of the parietal bone (C15 and C16).

Ideal sites for the bone graft

Of all 135 different locations, forty-seven (34.5%) and thirteen (9%) locations had an average thickness greater than 6 mm and 6.5 mm respectively. When locations within 2 cm from the midline were excluded, it further decreased to twenty-seven (20%) and three (2%) locations (Table 3).

Frequency of encountering a bone with an actual thickness of less than 6 mm was 20.6% (402/1947) in locations with an average thickness greater than 6 mm. The frequency decreased to 13% (71/539) in locations with an average thickness greater than 6.5 mm. No further improvement was seen thereafter by increased average thickness values (Table 4).

Table 1. Demographic data of study samples

Skulls	Age at death	Sex	Cause of death
1	72	F	Pneumonia
2	81	M	Lung cancer
3	62	F	Carcinomatosis
4	86	F	Cervical cancer
5	76	M	Chronic obstructive pulmonary disease
6	NA	M	NA
7	93	F	Congestive heart failure
8	89	F	Cardiac arrest
9	78	M	Lung cancer
10	75	M	Pneumonia and left ventricular failure
11	75	M	Gastrointestinal bleeding
12	NA	NA	NA
13	97	M	Cerebrovascular accident
14	65	M	Metastatic gastric carcinoma
15	NA	NA	NA
16	73	F	Respiratory cardiac arrest
17	77	F	Lung cancer
18	94	F	Cardiac arrest
19	79	F	Carcinomatosis of lung and liver
20	96	F	Congestive heart failure
21	78	M	Lung cancer
22	85	M	Colon cancer
23	75	M	Metastatic prostate cancer
24	81	F	Respiratory arrest
25	83	F	Cerebrovascular accident

Abbreviations: M = Male, F = Female, NA = Not available

Table 2. Average thickness of the parietal bones

	Thickness (+/- S.E.)	p-value
Overall average	6.69 (+/- 0.22) mm	
Ranges:		
- **Measurement**	2.55 mm – 13.1 mm	
- **Average of each point**	2.85 mm – 6.93 mm	
Gender variation:		
- **Male**	6.41 (+/- 0.30) mm	
- **Female**	Male + 0.54 (+/- 0.42) mm	0.20
Side variation:		
- **Right**	6.66 (+/- 0.22) mm	
- **Left**	Right + 0.06 (+/- 0.04) mm	0.21

Linear mixed model was used to estimate the averages

Univariate mixed model was used to compare sex and side variables

p-value = considered significant if less than 0.05

Abbreviations: S.E. = Standard error

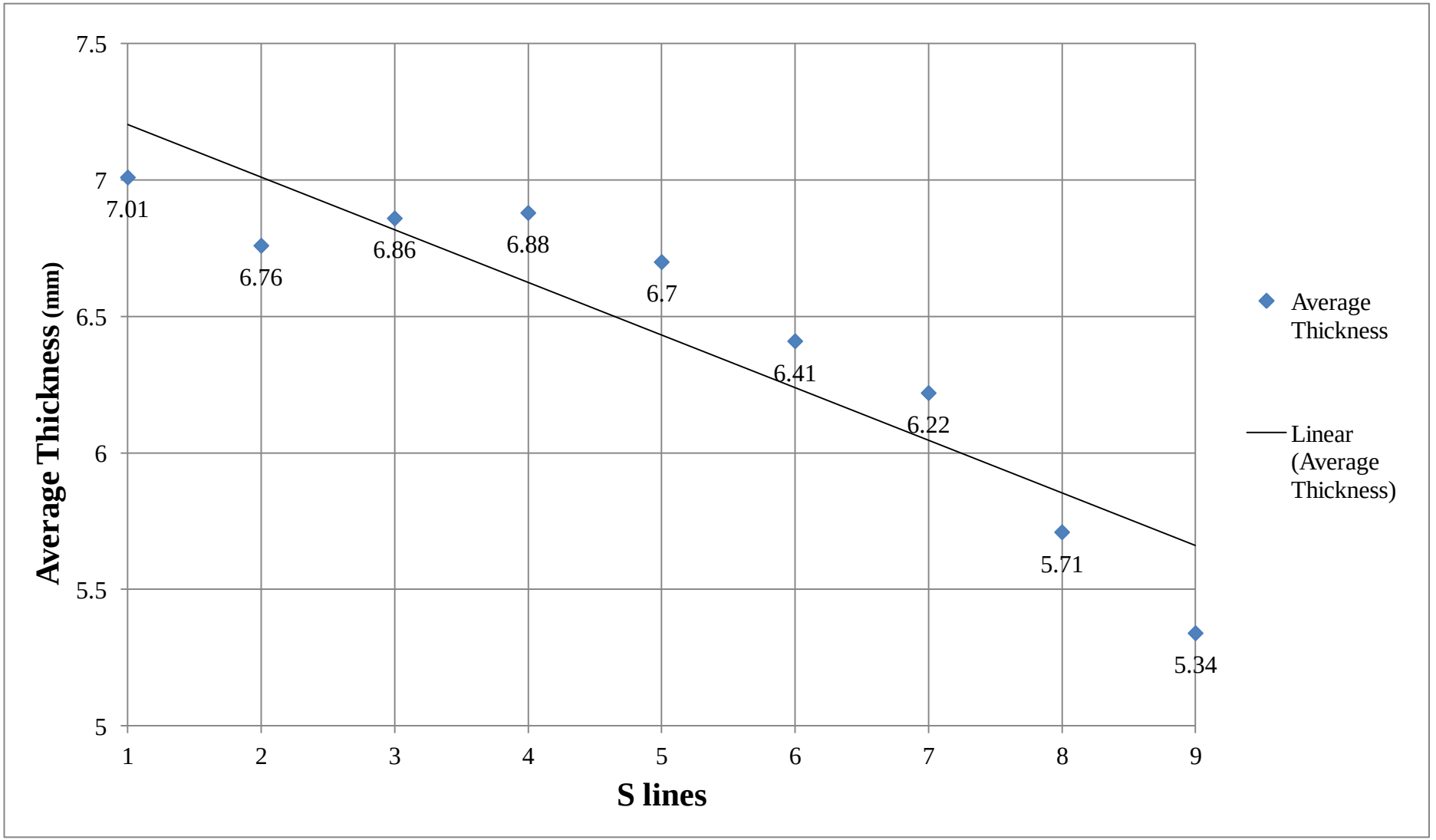

Figure 5. Scatterplot graph and line of best fit for average thicknesses of the parietal bone against the different S lines. Thickness is in millimetres. $R^2 = 0.83$

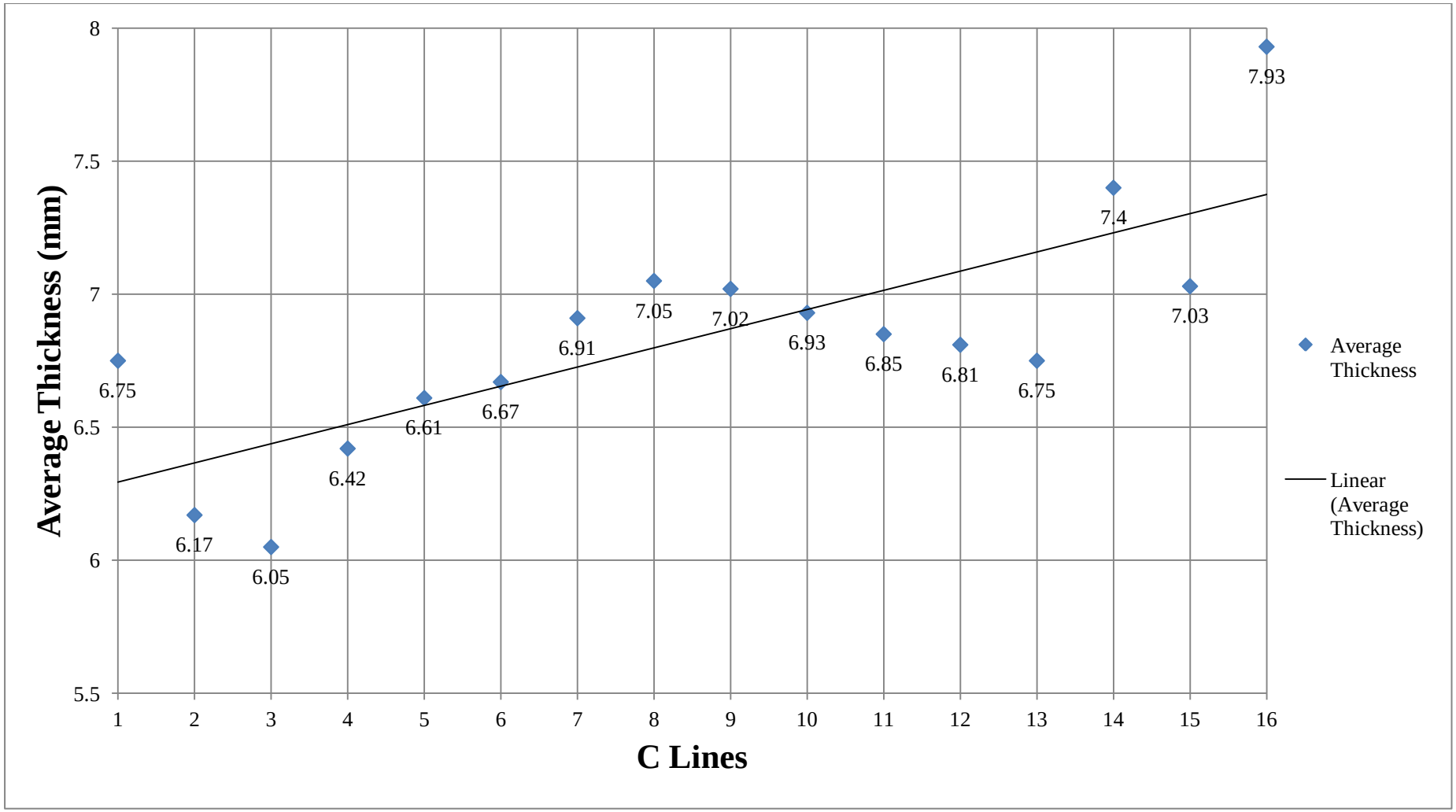

Figure 6. Scatterplot graph and line of best fit for average thicknesses of the parietal bone against the different C lines. Thickness is in millimetres. $R^2 = 0.56$

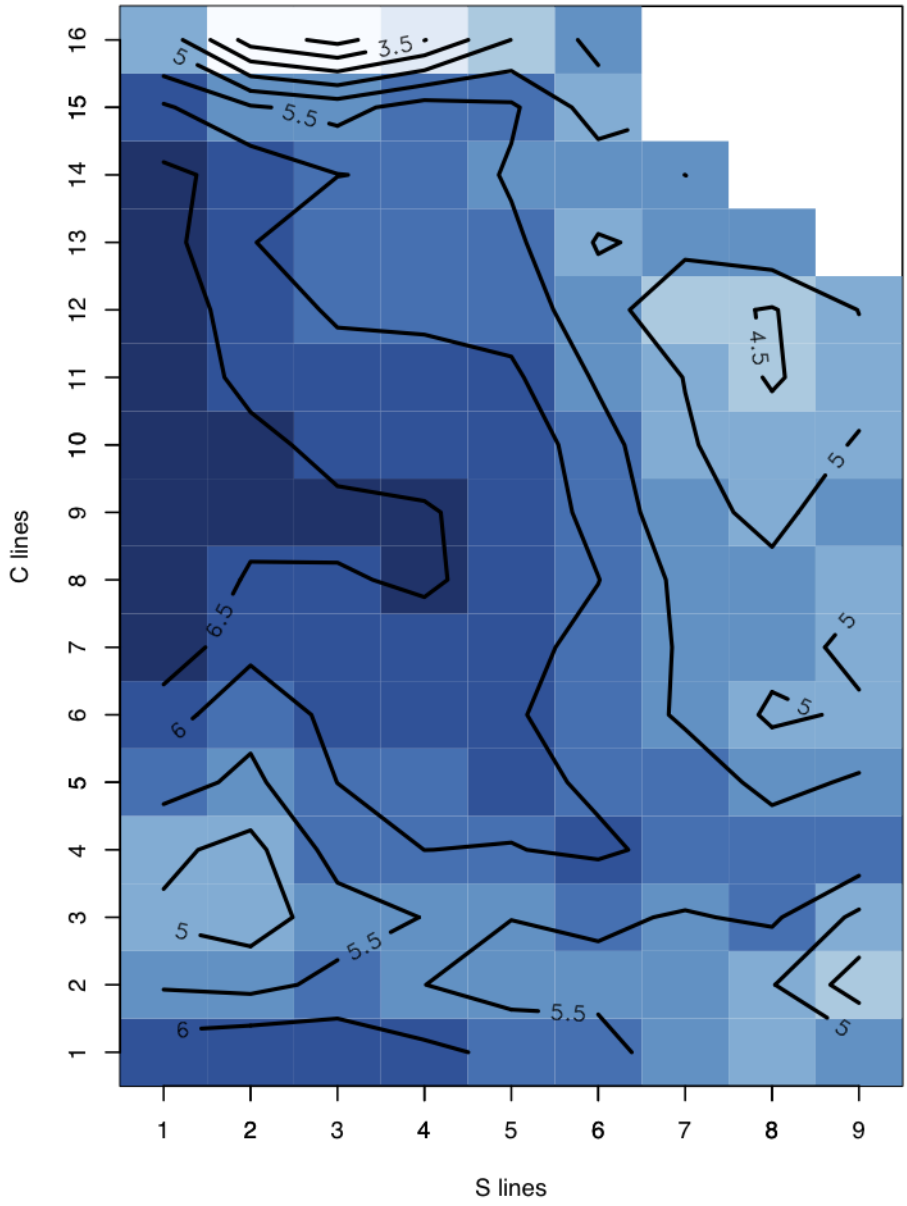

Figure 7. Thickness map showing regional variation in thickness of the parietal bone. Borders demarcate regions with average thicknesses of more than 6.5 mm, 6 mm, 5.5 mm, 5 mm, 4.5 mm, 4 mm, and 3.5 mm. Note a large U-shaped (bottom of U facing lateral direction) outline demarcating the area with an average thickness greater than 6 mm. A smaller U-shape outline (Bottom of U facing laterally and narrower) borders an area of an average thickness greater than 6.5 mm.

Table 3. Proportion of areas with an average thickness greater than 6 mm and 6.5 mm

Average thickness	**Proportions**
>6mm (all)	47/135 = 34.5%
>6mm (excluding S1 and S2)	27/135 = 20%
>6.5 mm (all)	13/135 = 9%
>6.5 mm (excluding S1 and S2)	3/135 = 2%

Table 4. Frequency of encountering bone with an actual thickness of less than 6 mm in different locations

Average thickness	**Frequency**
>6 mm	402/1947 = 20.6%
>6.5 mm	71/539 = 13%
>6.6 mm	38/355 = 10.7%
>6.7 mm	31/269 = 11.5%
>6.8 mm	22/179 = 12.3%

Discussion

Calvarial bone grafts are widely used in OMS. Although the complication rates are relatively low, the magnitude of the complications are potentially devastating for both patients and surgeons alike, highlighting the need for studies such as this to look at the thickness of the parietal bones in order to identify the safest site(s) for calvarial bone graft harvest. This report is unique from other studies in several ways in that: (1) this is the first New Zealand-based cadaveric study looking specifically at calvarial bone graft sites; (2) more locations were measured per parietal bone in comparison to other studies; (3) a thickness map was constructed so that exact locations are identifiable using anatomical landmarks; and (4) the identification of the safest sites was analysed to fit the features of ideal graft harvest sites described in the literature.

There are several limitations of this study. First and foremost is the limited number of specimens used in this study, in part due to the resources available during the study period. Secondly, only the skulls from the European ethnic group were used. The combination of these two limitations means that the sample cannot be representative of the New Zealand population but can only be taken as a sample. Furthermore, demographics have changed considerably over the last few decades and with the average age of the cadavers being in their eighties, once again the study sample cannot be seen as truly representative of a New Zealand population in the 21st century. Finally, the specimens may have come from individuals with bone-related disorders such as Paget's disease which could have caused an over-estimation of the parietal bone thickness. This information however was also unavailable.

In this report, the overall average thickness of the parietal bone was found to be 6.69 mm with an average thickness ranging from 2.85 mm to 6.93 mm in different regions. The results are comparable to the previous studies which reported ranges from: 4.73 mm to 6.67 mm in Koreans by Hwang et al;[7] 5.04 mm to 7.17 mm in another set of Koreans by Jung and colleagues;[8] and 5.3 mm to 7.5 mm in Caucasians and African Americans by Moreira-Gonzalez et al.[6] The upper range reported in the US-based study relates to thicker parietal bones found in African Americans compared to those found in Caucasians. The wider range reported in our study can be related to more measurements performed covering a greater area of the parietal bone in comparison to other studies. On average, seventy-eight points per skull

were measured in this report covering all regions of the parietal bone. The lines were only 1 cm apart with a maximum number of nine S lines and sixteen C lines. In comparison, Hwang et al[7] only had four lines of each, Jung et al[8] stopped well short of the lambdoid suture, and Moreira-Gonzalez et al[6] only measured twelve points per parietal bone with a lesser area of coverage.

The gender and side variable were found not to have any statistically significant association with the thickness of the parietal bone in this report. This differs from the finding reported by Moreira-Gonzalez et al[6] who found that the female had thicker bone than male.[6]

In terms of regional variations in thickness, this report was consistent with other studies with an observation of gradual thickening of the parietal bone in both medial and posterior directions. In medial direction, there was an average thickening of 0.2 mm per line proceeding from S9 to S1 line. In posterior direction, there was an average thickening of 0.07 mm per line proceeding from C1 to C16 line. The regional variation in thickness was clearly visible on the thickness map. The map shows a thicker region of the bone situating near the midline in the mid to posterior portion of the parietal bone. The overall, appearance of the map looks very similar to the ones created by Hwang et al[7] and Moreira-Gonzalez et al[6]. What is also apparent in the map is that there is a region with thin bone in the most posteromedial part of the parietal bone (along S1-5 and C15-16) which contradicts the finding that the bone becomes progressively thicker towards the posterior direction. Therefore, a more accurate description would be to say that the bone becomes progressively thicker in posterior direction but becomes thin again near the lambdoid suture. The same observation was seen in the map created by Moreira-Gonzalez et al.[6] Nevertheless, a multivariate analysis has failed to show any statistically significant differences in thickness among different points in this report. The negative result in this report is probably due to the points being too close to each other, anatomically, to detect any differences.

In regards to the ideal harvest sites, previous studies recommended bone graft to be harvested in posteromedial aspect of the parietal bone.[8] However, this description is very vague and subject to one's interpretation. Other studies have constructed a thickness map as a practical guide to surgeons at choosing the ideal sites.[6,7] Although such a map is ideal at locating regions with varying average thickness, it does not reflect on the features for the ideal harvest sites described in the literature as minimum thickness of 6 mm and 2 cm way

from the midline.[5,9,10] In regards to the former, the maps are excellent at showing the regions with an average thickness greater than 6 mm. However, what they do not show is the chance of encountering the bone with an actual thickness less than 6 mm in that region. Such chance or risk would be of more value to surgeons. In regards to the latter, the maps have no scales or anatomical landmarks to determine the distance of a particular region from the midline.

In this study, a significant proportion of parietal bone had an average thickness greater than 6 mm. However, a frequency of encountering bone with an actual thickness less than 6 mm in that region was 20.6% which may represent an unacceptably high risk. The frequency is reduced to 13% in the region with an average thickness greater than 6.5 mm. However, such a region is very scarce. In fact, only three (2%) locations in this report had an average thickness greater than 6.5 mm after excluding the locations within 2 cm from the midline. Therefore, it seems that the areas with an average thickness of 6 mm are less ideal due to the high risk of encountering less than 6 mm of bone. The areas with an average thickness of 6.5 mm are also not ideal as they are mostly situated within 2 cm from the midline.

Conclusion

The thickness and its regional variations in parietal bones of a New Zealand European sample are similar to those of other ethnic groups except for African Americans.

However, ideal bone graft sites that safely meet the recommendations of 6 mm of minimum thickness and 2 cm away from the midline were scarce. In regions with an average thickness greater than 6 mm, a frequency of encountering bone with an actual thickness less than 6 mm seemed too high. Although, the frequency is reduced in areas with an average thickness greater than 6.5 mm, most of the areas were located within 2 cm from the midline.

From this study, two recommendations are proposed: firstly, further studies are required to either validate or update the recommendations for ideal calvarial bone graft harvest sites and secondly, further prospective clinical studies in the use of preoperative imaging modalities could be of significant value in pre-operative planning and work up of patients requiring calvarial bone graft harvesting procedure.

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