UNIVERSITÉ FRANÇOIS - RABELAIS
DE TOURS

École Doctorale : Santé, Sciences, Technologies
Année Universitaire : 2009-2010

THÈSE

présentée par :

Boris LAURE

soutenue le : **26 novembre 2010**

pour obtenir le grade de : **Docteur de l'université François - Rabelais**
Discipline/ Spécialité : Sciences de la Vie

RESISTANCE DU CRANE APRES PRELEVEMENT CALVARIAL MONOCORTICAL

THÈSE dirigée par :

Monsieur François TRANQUART	PU-PH, Université François Rabelais, Tours

RAPPORTEURS :

Monsieur Arnaud PICARD	PU-PH, Université Pierre et Marie Curie, Paris 6
Monsieur Etienne SIMON	PU-PH, Université de Nancy

JURY :

Monsieur Cyrille CHOSSEGROS	PU-PH, Université de la Méditerranée, Marseille
Monsieur Christophe DESTRIEUX	MCU-PH, Université François Rabelais, Tours
Monsieur Dominique GOGA	PU-PH, Université François Rabelais, Tours
Monsieur Arnaud PICARD	PU-PH, Université Pierre et Marie Curie, Paris 6
Monsieur Etienne SIMON	PU-PH, Université de Nancy
Monsieur François TRANQUART	PU-PH, Université François Rabelais, Tours

Remerciements

Au Professeur Dominique GOGA, pour avoir initialisé ce travail et m'avoir soutenu dans sa réalisation,

Au Professeur François TRANQUART, pour m'avoir accepté dans son unité de recherche et accepté de diriger ce travail,

Au Professeur Stéphane VELUT, pour avoir accepté la réalisation de cette étude au Laboratoire d'Anatomie de la Faculté de Médecine de Tours,

A Laurent GEAIS, pour ses grandes qualités humaines et scientifiques,

Au Laboratoire Stryker et Adrien TREUILLE pour le financement de cette étude,

A Gilles GOMOT et au personnel de l'Institut National de la Recherche Agronomique de Nouzilly.

Au personnel du laboratoire d'anatomie de la Faculté de Médecine de Tours.

Résumé

Introduction

Le prélèvement crânien monocortical pourrait affaiblir la zone prélevée et exposer à des complications.

Matériel et Méthodes

Nous avons conçu un mouton pendule de Charpy validé sur 12 têtes de cadavres humains. L'énergie du choc était augmentée jusqu'à fracture de la zone pariétale. Pour mesurer l'épaisseur avec un système de navigation optoélectronique, nous avons comparé cinq méthodes non destructives.

Dans la deuxième partie, la quantification de la perte de résistance était réalisée sur 30 têtes humaines en comparant le choc maximal supportable avant fracture du côté prélevé avec le côté non prélevé.

La troisième partie de l'étude a été menée sur 34 têtes de cadavres de brebis.

Résultats

Le premier choc réalisé devait être au maximum de 4J. La méthode de mesure établie avait une précision de 0,1mm.

La perte de résistance de la zone prélevée était de 36% ($p=1.10^{-10}$) avec une diminution d'épaisseur de 40%. La corrélation entre les deux paramètres était modérée ($R=0.46$) mais significative ($p<0,0001$).

Chez la brebis, la diminution de résistance du côté prélevé était de 49% ($p=6.10^{-10}$).

Conclusion

La diminution de résistance du crâne chez l'homme et chez la brebis du côté prélevé est significative. Ces données nous permettrons de réaliser une étude animale, pour évaluer la résistance de la zone prélevée reconstruite par un ciment d'hydroxyapatite.

Résumé en anglais

Introduction

The monocortical parietal bone graft could decrease the strengh of the donor site. Complication could occur.

Materiel and Methods

We performed a Charpy impact machine and validated it on 12 human cadaver heads. The chock energy was increased until the fracture of the target zone. The thickness measurement was performed with an optoelectronic navigation device. We compared 5 non destructive methods. In the second part, the quantification of the resistance loss was performed on 30 human cadavers heads. The maximum impact resistance of bone on the donor side was compared with the intact side. The third part of the study was performed on 34 sheep cadaver heads.

Results

The first chock had to be 4 J. The measurement method was established to an accuracy of 0.1 mm.

Loss of strength at the donor site was 36% ($p=1.10^{-10}$) for 40% loss of thickness. Although correlation between these two parameters was rather moderate ($R=0.46$), it was highly significant ($p<0.0001$).

On sheep, the loss of strength at the donor site was 49% ($p=6.10^{-10}$).

Conclusion

Bone removal results in a highly loss of strength on human and sheep. These data will permit to perform an animal study to evaluate the resistance of the harvest cranial zone rebuilt with hydroxyapatite cement.

Table des matières

Introduction

Les greffes osseuses sont utilisées depuis longtemps en chirurgie. Les sites donneurs sont divers (côtes, crête iliaque, tibia…). En chirurgie cranio-maxillo-faciale, l'os pariétal est un site donneur particulier à cette spécialité (*Raulo 1990*).

L'os pariétal est un os pair, plat, participant à la formation de la voûte du crâne. Il s'articule avec l'os frontal en avant, l'os sphénoïde en avant, les os temporaux en bas, l'os occipital en arrière, l'os pariétal controlatéral en haut, au niveau de la ligne médiane le long de la suture sagittale (Fig 1 et 2). Les os pariétaux ont une forme rectangulaire légèrement incurvée, formant la voûte crânienne. Sur la face interne (au contact des méninges) on voit le cheminement de l'artère méningée moyenne, le passage du sillon du sinus longitudinal supérieur en haut, et le passage du sillon du sinus sigmoïde en arrière. La face externe (au contact du cuir chevelu) est parcourue par les lignes temporales sous lesquelles s'insère le muscle temporal. Il existe quatre bords et quatre angles.

Un des intérêts majeurs du greffon d'os pariétal découle directement de l'origine embryologique et de la physiologie de l'os membraneux. Plusieurs auteurs ont démontré un comportement et une physiologie différents entre les deux types d'ossification (*Smith 1974, Zins 1983, Kusiak 1985)*. L'os membraneux se résorbe moins et se revascularise plus vite que l'os enchondral (côtes, tibia, os iliaque). Les autres avantages de cet os (*Harsha 1986, Jackson 1983,1986)* sont une quantité d'os spongieux suffisante chez l'enfant, la possibilité d'avoir le site de prélèvement dans le même champ opératoire, le prélèvement est rapide, les douleurs post-opératoires sont minimes, un séjour hospitalier raccourci par rapport à la greffe iliaque. La cicatrice est invisible cachée dans les cheveux, la morbidité est faible et le saignement minime.

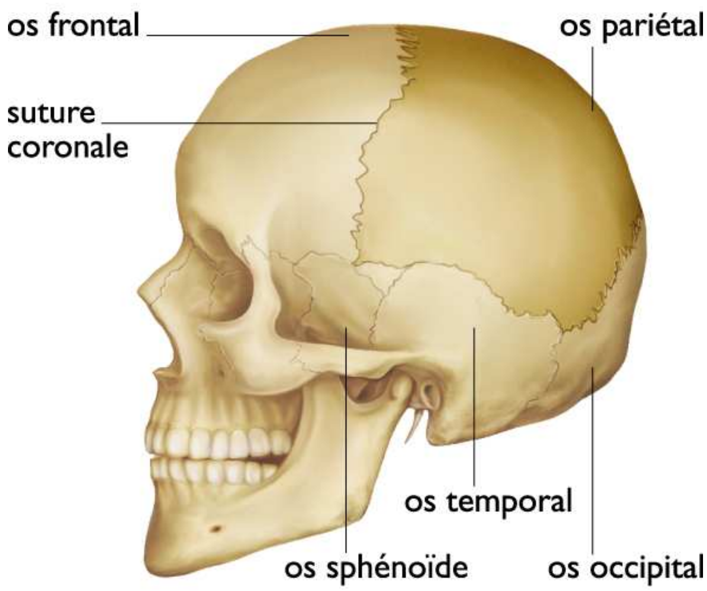


Fig 1 : Vue latérale gauche du crane et de la face osseuse

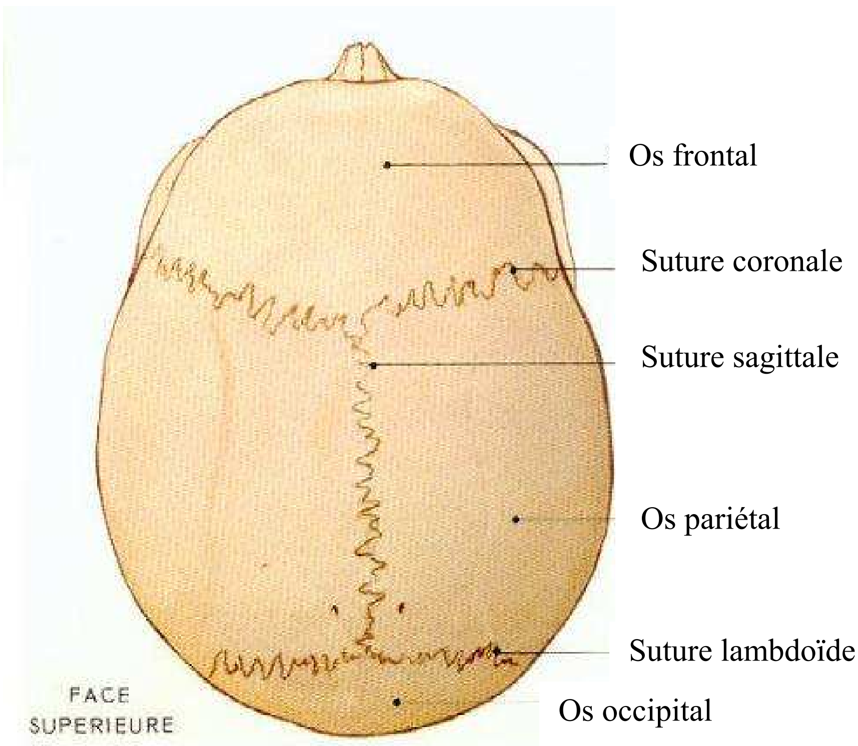


Fig 2 : Vue supérieure de la calvaria

Il existe cependant des inconvénients : la proximité des champs opératoires n'autorise pas le travail à 2 équipes et prolonge le temps opératoire, l'os spongieux est en faible quantité chez l'adulte, il existe une risque brèche méningée occulte, la cicatrice est visible si le patient est alopécique, et il persiste une dépression palpable au niveau du cuir chevelu.

En chirurgie réparatrice osseuse de la face, ces greffes pariétales sont utilisés dans différentes indications : en chirurgie pré-implantaire (*Baccar 2005, Crespi 2007, Fleuridas 1998, Grenadier 1992,Gutta 2008, 2009, Iizuka 2004,Le Lorc'h-Bukiet 2005*), en chirurgie orbitaire (*Melega 1984, Siddique 2002, Wolfe 2008*), dans la chirurgie des malformations faciales (*Cohen 1991, Eichhorn 2009, Siciliano 1995, Wolfe 1983*), ou chirurgie esthétique de la face (*Dupoirieux 1994*, Himy 2009, *Krastinova-Lolov 1995, Maniglia 1993, Shipchandler 2008, Zanaret 1999*).

La technique de prélèvement du greffon est bien codifié (*Tessier 2005, Tulasne 2003*). Les repères pour le prélèvement pariétal sont 10mm en arrière de la suture coronale pour éviter la zone de la suture où le clivage est difficile et 20mm en externe de la suture sagittale pour éviter la blessure du sinus sagittal supérieur qui pourrait avoir des conséquences désastreuses. La corticale externe est fraisée à la fraise d'un diamètre plus ou moins gros selon les opérateurs jusqu'à la diploé (Fig 3). Le greffon est ensuite levé au ciseaux à os dans le plan de la diploé. La surface du greffon varie en fonction du manque osseux à greffer mais la totalité de la voute pariétale peut être prélevée.

Ce prélèvement de la table externe pariétale diminue l'épaisseur de la voûte (Fig 5, Fig 6a et 6b). Cette diminution d'épaisseur pourrait donc potentiellement réduire la résistance au choc de la zone prélevée et constituer de ce fait une zone de faiblesse exposant à des complications délétères (*Kline 1995*).

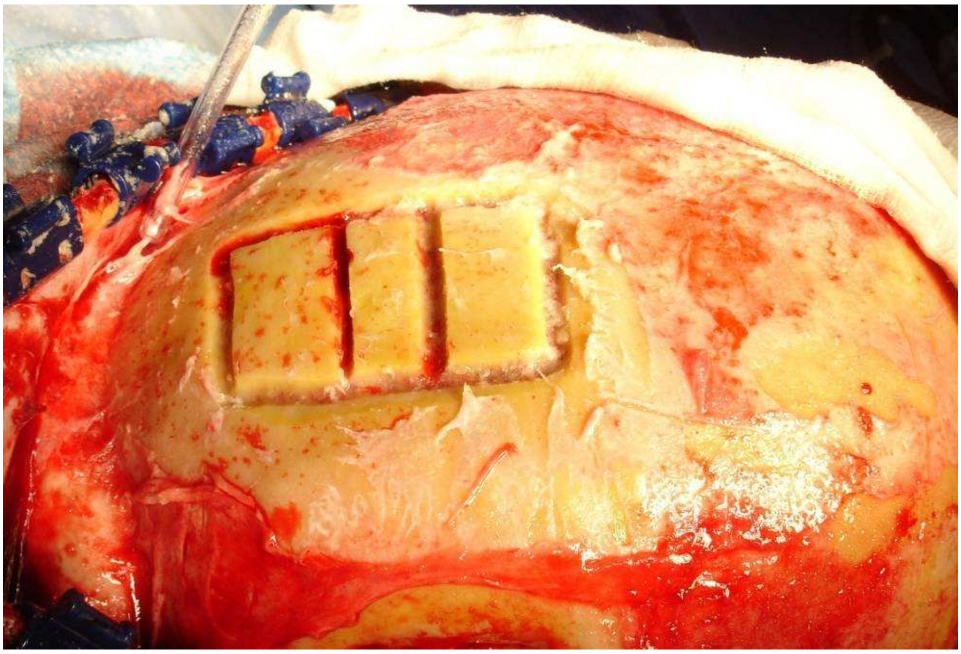


Fig 3 : L'os pariétal est fraisé jusqu'à la diploé

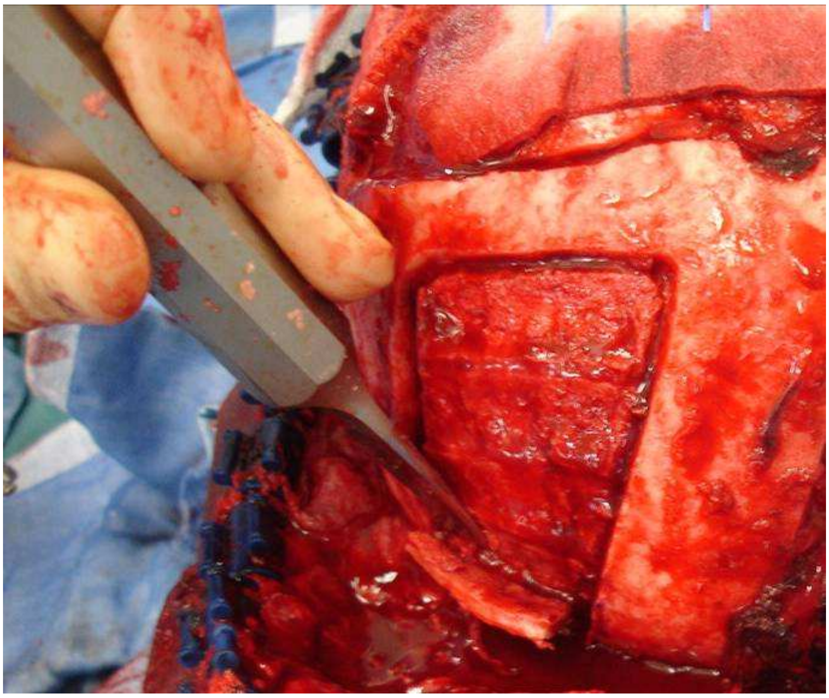


Fig 4 : prélèvement du greffon parietal aux ciseaux à os de Tessier

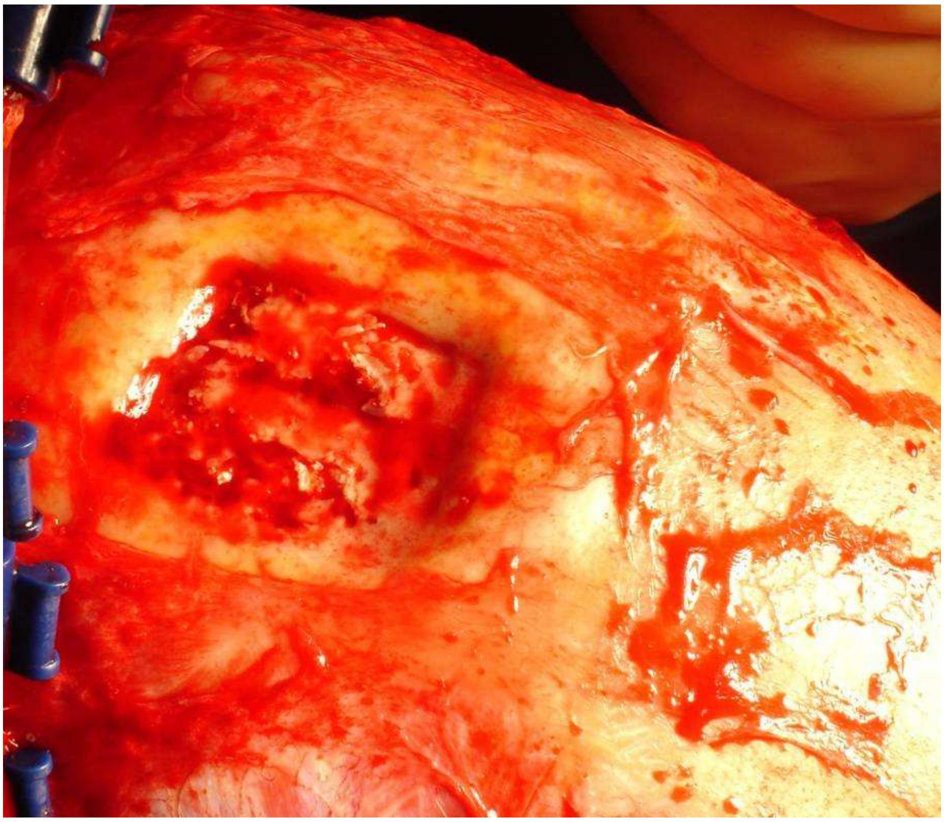


Fig 5 : Aspect du site opératoire 2 ans après un prélèvement pariétal

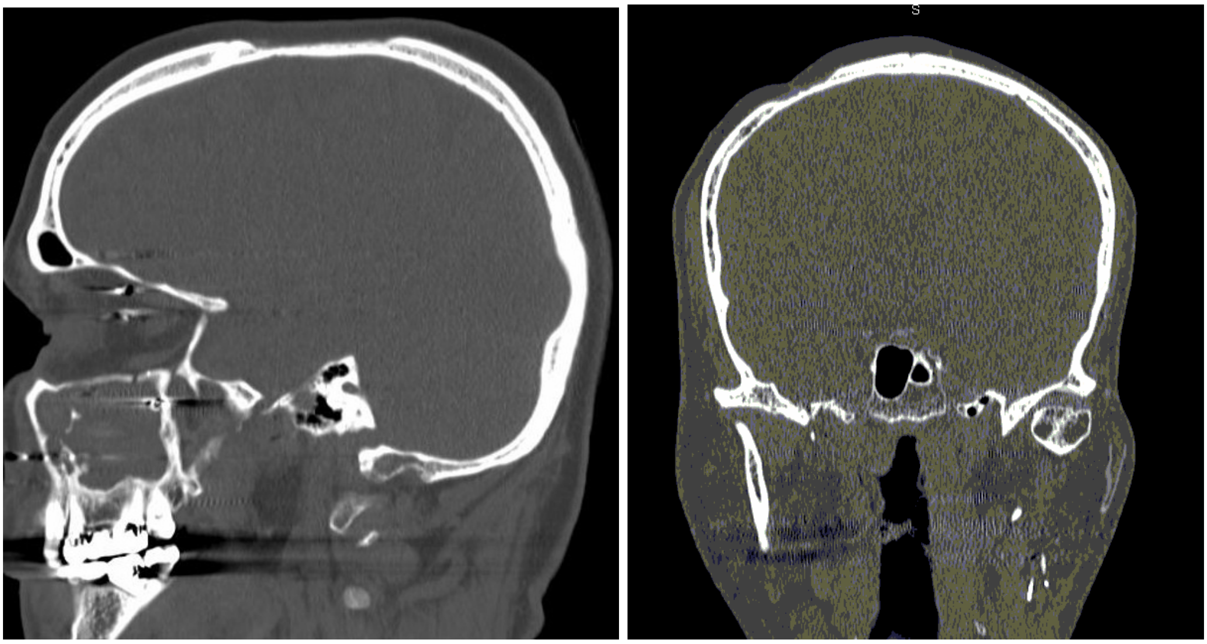


Fig 6a et 6b : aspect au scanner en coupe parasagittale et coronale deux

ans *après* prélèvement pariétal : l'épaisseur de la voûte est diminuée

En peropératoire, le risque encouru est essentiellement lié au geste chirurgical et peut être une perforation de la table interne (entre 10% et 11% d'après les travaux de Kline (*Kline 1995*), 15% pour Fearon (*Fearon 2000*). Pour un opérateur formé et expérimenté, cette complication est occasionnelle et peu dommageable. En revanche des complications plus graves ont été rapportées dont une plaie du sinus sagittal supérieur (*Cannella 1990*) et un hématome intracérabral (*Young 1990*). Dans une étude rétrospective, Wolfe a trouvé un taux de complication global de 0,18% *(Kline 1995)*. Keen (*Keen 1995*) suggérait que les complications locales étaient de 3% à 5% et de 1% pour les complications neurologiques.

En post opératoire, on ne connaît pas aujourd'hui réellement les conséquences possibles d'une telle baisse de résistance de l'os pariétal pour le patient. Cependant, selon notre connaissance, nous savons qu'un jeune patient qui avait eu une greffe osseuse pariétale à visée préimplantaire est mort après un choc sur la zone prélevée. L'autopsie a révélée un hématome extra-dural avec une fracture de la zone prélevée en regard. Cependant à notre connaissance, ce cas n'a jamais été rapporté dans une revue médicale.

Actuellement, la pression juridique conduit le chirurgien à mesurer pour chacun de ses actes le risque encouru par le patient et le bénéfice attendu, qu'ils soient immédiats ou retardés, surtout s'il s'agit d'une chirurgie non vitale.

Il nous a donc paru intéressant d'évaluer le lien entre l'épaisseur de la zone de prélèvement et la résistance au choc. La résistance au choc de cette zone pariétale après prélèvement n'a jamais été évaluée.

Les études expérimentales menées en biomécanique des chocs sur les fractures de la face et du crâne consistent à reproduire une configuration précise d'impact sur un sujet post-mortem (ou sujet anatomique), afin d'évaluer sa réponse. Les objectifs de ces études sont la détermination de critères de blessures et de seuils de tolérance, pour différents os du crâne et de la face, selon divers chargements (*Allsop 1988, Hodgson 1967, Nahum 1968*), la définition de corridors de comportement, c'est à dire de courbes de réponse à une sollicitation, de type infra lésionnelle ou bien lésionnelle (*Bruyere 2000, Melvin 1989*), l'évaluation de l'influence de paramètres tels que le mode de conservation, la minéralisation, l'âge ou le sexe des sujets, sur la réponse mécanique (*Allsop 1991, Nahum 1968, Schneider 1972*).

Les chargements dynamiques sont réalisés soit à l'aide de bancs verticaux autorisant la chute d'une masse impactante sur la pièce anatomique (ou bien la chute de la pièce anatomique elle-même), soit à l'aide d'impacteurs horizontaux guidés. Les dispositifs expérimentaux, permettant d'appliquer un chargement statique, sont des systèmes de presse hydraulique ou bien mécanique.

Les surfaces impactantes ont une géométrie variant d'une étude à l'autre. Certains auteurs utilisent des surfaces planes, dont l'influence des dimensions sur la réponse est étudiée, tandis que d'autres privilégient des éléments présents dans un véhicule automobile (tableau de bord, volant).

L'influence de la superposition d'un matériau amortissant à la surface impactante est également étudiée.

Les mesures réalisées sont l'effort, la vitesse, l'accélération et le déplacement.

La variabilité importante des conditions d'essais (localisation du choc, géométrie de la surface impactante…) rend la synthèse des résultats difficile.

Des seuils de tolérance en terme d'effort ou bien d'énergie d'impact sont déterminés pour les différents os de la tête (frontal, zygomatique, nasal, pariétal…) (*Allsop 1988, Bruyere 2000, Hodgson 1967, Nahum 1968, Ono 1980,, Schneider 1972*). Les études expérimentales donnent également des corridors de réponse mécanique en terme d'effort ou bien d'accélération (*Bruyere 2000, Melvin 1989).*

Il ressort également de ces études les observations suivantes : la géométrie de la surface impactante influence fortement la réponse mécanique. L'étude menée par Hodgson montre que la tolérance augmente avec l'aire de contact (*Hodgson 1967*). Yoganandan démontre que l'addition de matériaux amortissants, dont la surface de contact se déforme durant le choc, agit sur le seuil de tolérance (*Yoganandan 1988*). Plusieurs auteurs indiquent aussi que le type de fracture dépend de la géométrie de l'impacteur (*Allsop 1991, Hodgson 1967, Melvin 1971).* Le sexe de l'individu est un paramètre important : les femmes ont une tolérance moindre (*Nahum 1968, Schneider 1972)*. Les paramètres agissant sur le seuil de tolérance sont l'énergie cinétique, la vitesse d'impact, et l'effort (*Nyquist 1986*). Les avis sont partagés concernant l'influence de l'embaumement (*Nahum 1968, Schneider 1972)*. La composition minérale (*Allsop 1991)* n'est pas un paramètre agissant sur la tolérance au choc des individus. L'accélération de l'impacteur n'a également aucune influence sur le seuil de tolérance (*Hodgson 1970).*

Deux grands types de méthodes d'évaluation de la résistance au choc étaient possibles. La première est la méthode dite des éléments finis dynamique (DFEA) (*Auturi 2006, Kleiven 2002*). Un modèle virtuel du crâne est créé (par exemple à partir de coupes de tomodensitométrie X (TDM) (*Kleiven 2002)*, ou de données morphométriques (*Camacho 1997, Motherway 2009, Willinger 1999*). Pour être pertinent, ce modèle doit être obligatoirement validé par une expérimentation préalable.

La seconde méthode est l'expérimentation réelle avec réalisation de chocs quantifiés pour évaluer la déformation subie par l'os du crâne.

Plusieurs types de montages et de tests ont été décrits pour évaluer la résistance au choc de l'os frontal : tour de chute (*Hodgson 1970*), piston hydraulique utilisé pour percuter la tête (Yogananadan 2004) et le mouton pendule de Charpy (*Verschueren 2007*). La méthode de chute libre (tour de chute) présente l'inconvénient de ne pas définir précisément de zone d'impact. La méthode avec le piston hydraulique à l'avantage de viser avec précision le point d'impact. Il présente l'inconvénient d'appliquer une force progressive et ne permet pas de tester la résistance au choc. Le mouton pendule de Charpy permet d'atteindre précisément la zone d'impact et un calcul simple de l'énergie (E=mgh). .

Le montage que nous avons retenu pour tester cette résistance au choc était le mouton-pendule de Charpy.

L'essai de flexion par choc sur éprouvette entaillée Charpy (*Charpy 1901*) a pour but de mesurer la résistance d'un matériau à la rupture brutale. Il est appelé essai de résilience Charpy. Cet essai est destiné à mesurer l'énergie nécessaire pour rompre en une seule fois une éprouvette préalablement entaillée. On utilise un mouton-pendule muni à son extrémité d'un couteau qui permet de développer une énergie donnée au moment du choc. L'énergie absorbée est obtenue en comparant la différence d'énergie potentielle entre le départ du pendule et la fin de l'essai. La machine est munie d'index permettant de connaître la hauteur du pendule au départ ainsi que la position la plus haute que le pendule atteindra après la rupture de l'éprouvette. L'énergie obtenue (en négligeant les frottements) est égale à :

$K = m.g.h - m.g.h'$

m : masse du mouton-pendule

g : accélération de la pesanteur (environ 9.81 $m.s^{-2}$)

h : hauteur du mouton-pendule à sa position de départ

h': hauteur du mouton-pendule à sa position d'arrivée

La première partie de notre travail avait deux objectifs : le dimensionnement d'un montage expérimental de mesure des chocs, et la détermination d'une méthode de mesure des épaisseurs de la voûte pariétale avant et après prélèvement.

Première partie :

<u>Caractérisation mécanique et mesure optoélectronique de l'épaisseur de la voûte pariétale avant et après prélèvement monocortical : développement et validation d'un protocole d'essai.</u>

Résumé :

Introduction

Le prélèvement crânien pariétal est couramment utilisé en chirurgie cranio-maxillo-faciale. Ce prélèvement pourrait affaiblir la zone pariétale et exposer à des complications délétères.

Le but de notre étude était de rédiger un protocole d'essai de caractérisation de la résistance au choc de l'os pariétal avec et sans prélèvement monocortical externe, et de valider une mesure optoélectronique de l'épaisseur pariétale.

Matériel et Méthodes

L'étude de validation de ce protocole a été réalisée sur 12 têtes fraîches de cadavres humains.

Pour étudier la résistance au choc, nous avons conçu un mouton pendule de Charpy. Pour chaque tête, l'énergie du choc était augmentée progressivement jusqu'à la fracture de la zone pariétale définie. Le protocole de caractérisation consistait à mesurer l'énergie absorbable avant fracture. Pour mesurer précisément l'épaisseur pariétale, nous avons comparé cinq méthodes non destructives à l'aide d'un système de navigation optoélectronique.

Résultats

Notre montage permettait de mesurer la résistance de la voûte pariétale au choc avec une précision de 0,025J. Nous avons pu définir la plage de valeurs de chocs admissibles et plus particulièrement sa borne inférieure. Le premier choc réalisé devait être au maximum de 4J.

Les résultats des essais de mesures ont abouti à un algorithme basé sur deux méthodes permettant d'obtenir une précision de mesure de 0,1mm.

Conclusion

La validation de ce protocole nous permettra d'étudier ultérieurement la perte de résistance due au prélèvement pariétal et les liens entre l'épaisseur et la résistance de l'os pariétal.

Mechanical characterization and optoelectronic measurement of parietal bone thickness before and after monocortical bone graft harvest: design and validation of a test protocol

Boris LAURE, MD (a, b), Laurent GEAIS (a), François TRANQUART, MD, PhD (b), Dominique GOGA, MD(a)

(a) Service de Chirurgie Maxillo-faciale et Plastique de la Face, Université François Rabelais, Hôpital Trousseau CHRU Tours, 37044 Tours cedex

(b)Unité Médicale Ultrasons INSERM U930-CNRS 2448 Université François Rabelais Hôpital Bretonneau CHRU Tours- 37044 Tours Cedex

Corresponding author :

Dr Boris LAURE
Servive de Chirurgie Maxillo-faciale
CHU Trousseau
37044 Tours cedex, France
Phone : + 33 247 474 640
Fax : +33 247 478 529
Mail : laure@med.univ-tours.fr

No funding were received for this work from any of the following organizations: National Institutes of Health (NIH); Wellcome Trust; Howard Hughes Medical Institute (HHMI)

Sources of support: Sryker compagny supported this study

Summary

Parietal bone grafts are commonly used in craniomaxillofacial surgery. However, removing bone may weaken the parietal bone and lead to deleterious complications. The aim of our study was to design a test protocol for characterization of the impact resistance of parietal bone before and after monocortical bone graft harvest, and to validate an optoelectronic measurement of parietal bone thickness.Twelve fresh human cadaver heads were used for the validation study.

To evaluate impact resistance, we developed a pendulum Charpy impact testing machine.

The impact force was gradually increased until failure (fracture) of the defined parietal bone area. According to the protocol, we measured the maximum absorbable energy or impact force to failure. With our test set-up, measurement of the impact resistance of parietal bone was accurate to within 0.025 J. We defined a range of values and particularly a threshold value. The initial maximal impact must not to exceed 4 J.

For more accuracy, we compared 5 nondestructive measurement methods using a surgical navigation system with optoelectronic tracking. We achieved an algorythm based on two methods that ensured a measurement resolution of 0.1 mm. Validation of this protocol will allow us to evaluate the loss of strength resulting from bone removal, and the correlation between strength and thickness of the parietal bone

Key words: parietal bone, bone transplantation, skull fracture, resistance training

Introduction

Autologous bone grafts obtained from the outer table of the parietal bone are commonly used for craniomaxillofacial reconstruction[1-3]. Main indications include: pre-implant procedures, orbital surgery[4], facial deformities, or facial cosmetic surgery[5-6]. Removing bone from the outer table decreases thickness of the calvaria and may potentially affect impact resistance at the donor site. .

Late postoperative complications have never been reported. Only preoperative or early complications are discribed[7]. Nevertheless, we performed this study as a result of our knowledge of a patient who, following a calvarial bone graft, died after sustaining a traumatic injury to his skull. His death was caused by an extra dural hematoma. The autopsy revealed a fracture of the calvaria on the site of the cranial bone harvest. This case has never been reported in a medical journal.

Currently, due to strong legal pressure, surgeons carefully weigh the risks incurred by the patient against the expected benefits (whether immediate or deferred), particularly for non-vital surgery.

It would be interesting to evaluate the relationship between thickness and impact resistance of the donor site. A correlation study might be initiated later on.

This study had two primary aims: develop a test set-up to measure impact forces and determine the most appropriate method for measuring parietal bone thickness before and after bone graft harvest.

First of all, we had to determine load values. No information was available in the scientific literature. We then had to develop an initial set-up to determine these values.

For thickness measurements, we selected to use a navigation system. Many measurement methods were available. We identified and evaluated 5 methods.

The following section describes the development and validation of a set-up for cadaver head impact testing and thickness measurement.

Materials and Methods

Specimen preparation

Twelve fresh human cadaver heads (non-frozen, unembalmed heads) were used for this study which was conducted at the Anatomy division of the University School of Medicine (Tours, France) in compliance with ethical rules as regards human experimentations on people who have donated their body to science. All adult specimens were free from calvarial injuries or bone diseases.

The study population consisted of 7 males (58%) and 5 females (42%).

Age at death ranged from 74 to 97 years, with a mean of 83 years (SD = 7 years).

All tests were performed between 4 and 21 days after the death with a mean of 9 days (SD = 5 days).

The entire scalp was removed and the calvaria was exposed after elevation of periosteum. Landmarks for bone graft harvest on the right side were: 10 mm posterior to the coronal suture and 20 mm lateral to the sagittal suture. The harvest area measured 40 mm x 40 mm (1600 mm^2) (Fig.1), which corresponds to the size of parietal bone grafts used in clinical practice. The outer table was reamed down to the diploe (on the right side only) using a round burr. The parietal bone was then split with sharp bone splitters using the Tessier technique[3]).

Identical markings were made on the control left side which remained intact.

After destructive impact, a calvarial bone flap was obtained (using a milling machine) on both sides for thickness measurements. The destructive impact was defined by a visual linear crack or depressed skull fracture.

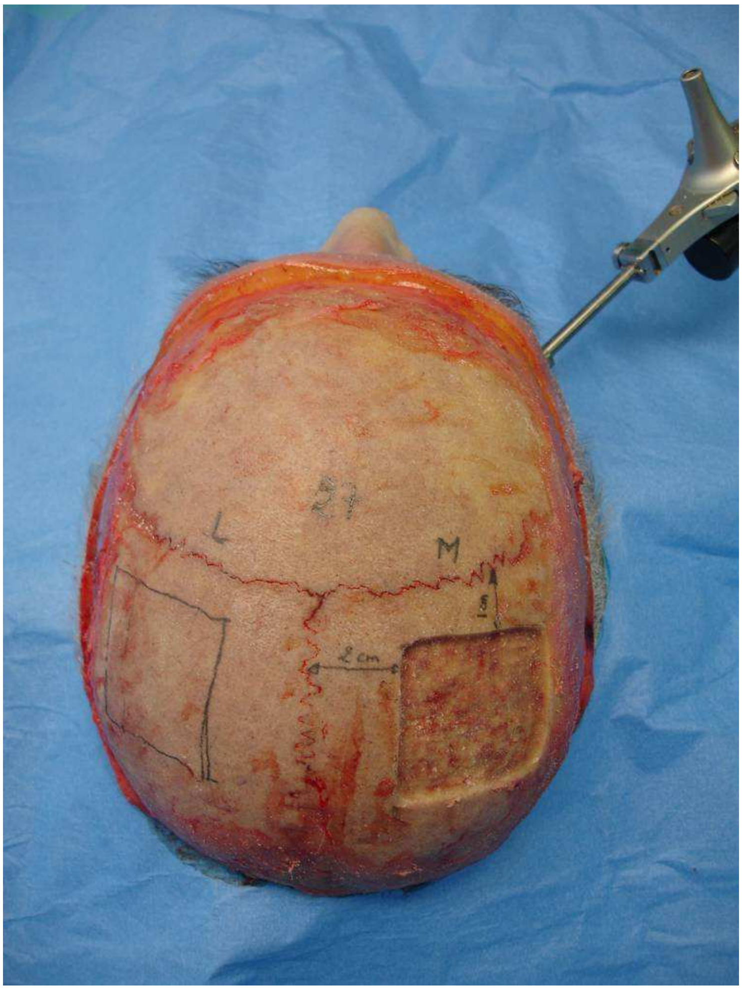
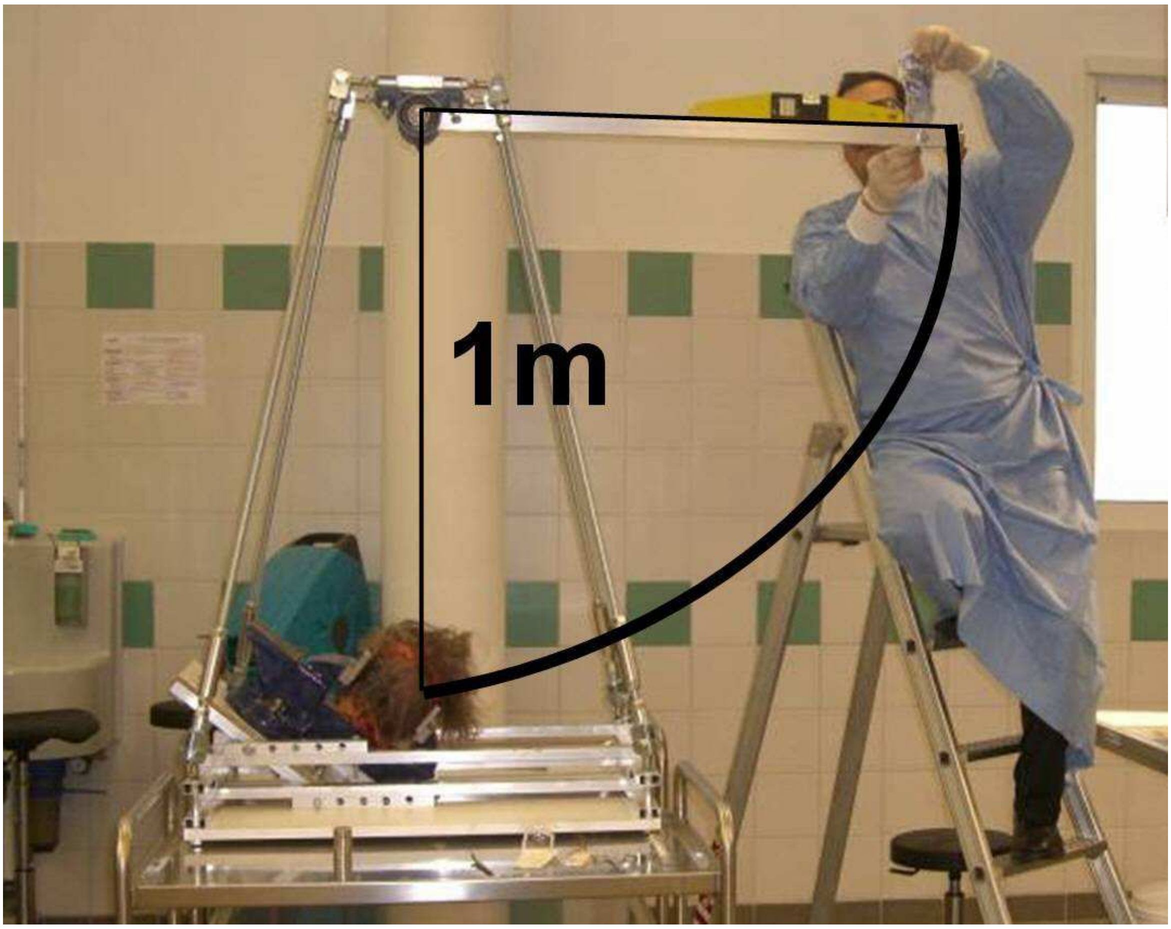


Figure 1: Right and left parietal bone areas – Tracker

Test set-up for impact force measurement

We developed a pendulum Charpy impact testing machine to quantify the maximum absorbable energy or impact force to failure (parietal bone fracture), using the left side for control (Fig. 2a).

The swinging pendulum (Fig. 2b) was 1 m long (i.e. distance between its axis of rotation and the center of the hammer). The hammer was released from a height of one meter and stroke a defined target zone. In order to minimize energy loss due to friction and deformation, the whole set-up including the head fixation system was optimized to achieve a rigid construct. Stability of the set-up was provided by a pyramid-shape four-legged frame (Fig. 2a). At the beginning of each test, the pendulum was in a horizontal position (checked with a spirit level) (Fig. 2b). Thus, the potential initial energy of the raised mass was considered to be totally absorbed during impact.



Figures 2a and 2b: Test Set-up

The total initial mass was 0.820 kg. The energy generated by this mass accelerated to 1 m was 8.0 J.

Load was gradually increased by adding washers weighing 25 g each. Therefore, accuracy of energy measurement was 0.025 J. After each impact, the total raised mass (i.e. hammer + washers + axes + nut + arm) was checked using a digital force gauge (Mark-10 BG20E – Vitrolles, France, with an accuracy of ± 0.2%).

Speed of the hammer at impact was: $v = \sqrt{2gh} = 4{,}43 m/s$ (g (gravity) = 9.812 m/s^2, h (height of drop) = 1 m). Verschueren [8] performed two tests at 5.3 m/s.

The parietal target zone was a square of side length 40 mm. To fit this area, we used a 28.7 mm diameter (surface of a square inch = 645 mm^2) hammer similar to that used by Yoganandan[9].

The set-up had been specially designed to deliver the impact right in the center of the target zone, with the hammer surface parallel to the target zone. To meet these two requirements, 6 degrees of freedom were necessary. The test specimen was rigidly fixed in a vice. The first set of impacts was delivered to the donor right side. Then, the specimen was placed on the other side to deliver a second set of impacts to the intact left side (control). Thus, we had two paired series.

A digital camera was placed at a distance of 4 m from the test set-up to record each impact at a frame rate of 24 frames/s (one frame every 42 ms), with 640x480 pixel resolution. It allowed to check the absence of bounce at impact.

Thickness measurement

A surgical navigation system (Stryker Leibinger Cart 1, Pusignan, France) with a dedicated software was used. This system allows selection of points in space and digitization of these points using a pointer and a tracker fixed to the bone. We selected 25 points on the first layer (outer table), 25 points on the second layer (diploe), and 16 points on the third layer (periphery of the inner table) (Fig. 3). This method allowed to measure the thickness of the outer table at 25 points and that of the inner table at 16 points. These 16 points were collected after removal of the inner table, once the last impact had been delivered.

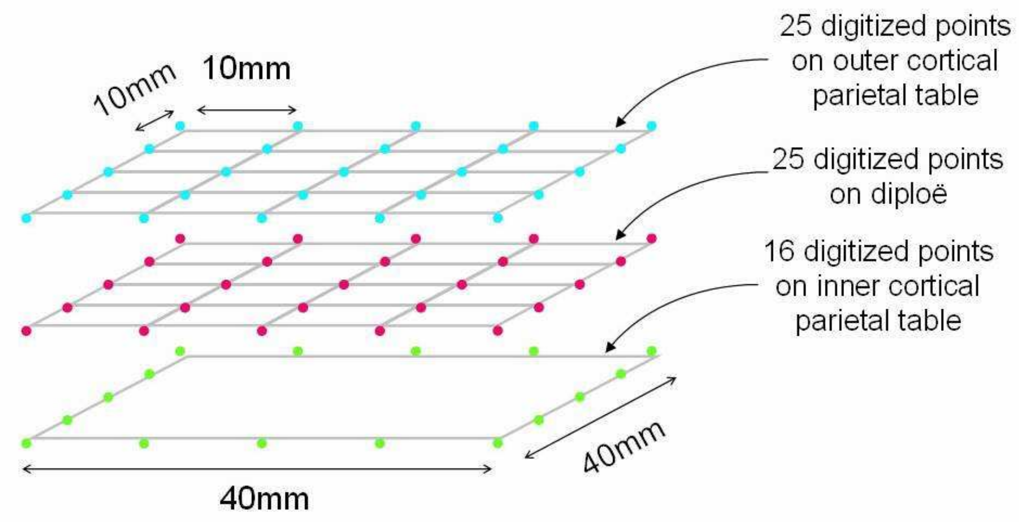


Figure 3: Digitized points for calculation of thickness

Due to the curved and irregular surface of the inner and outer parietal tables, it was necessary to geometrically define the thickness. Five geometric definitions were compared.

1st definition

At each point, thickness was defined as the distance between the points digitized on the three layers (Fig. 4a). This method is simple but highly sensitive to misalignment. Any misalignment of the outer and inner surface points inevitably leads to inaccurate calculation. Thickness was systematically overestimated. This method is similar to that used by Telliogu[10].

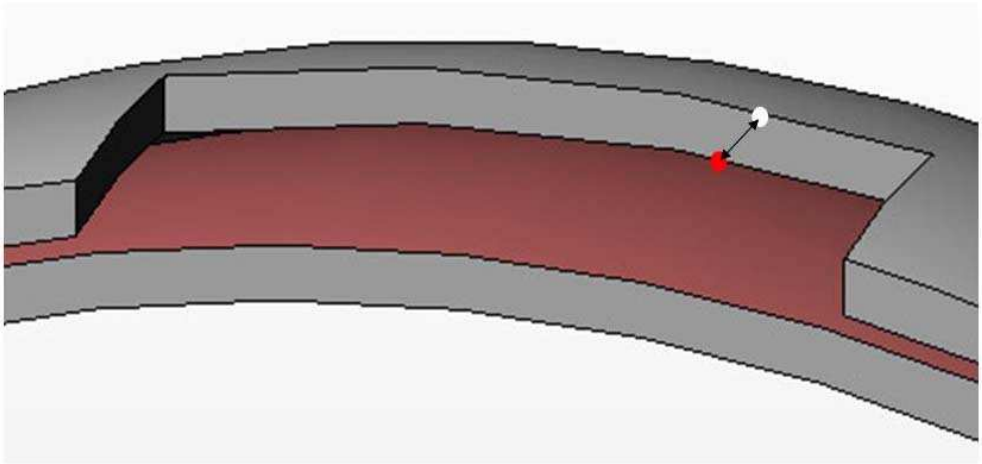


Figure 4a: Measurement of skull thickness using Method 1

2nd definition

The intact outer surface was considered a reliable reference. We drew a local normal for each point. Thickness corresponded to the distance between projections of the digitized points on this local normal (Fig. 4b).

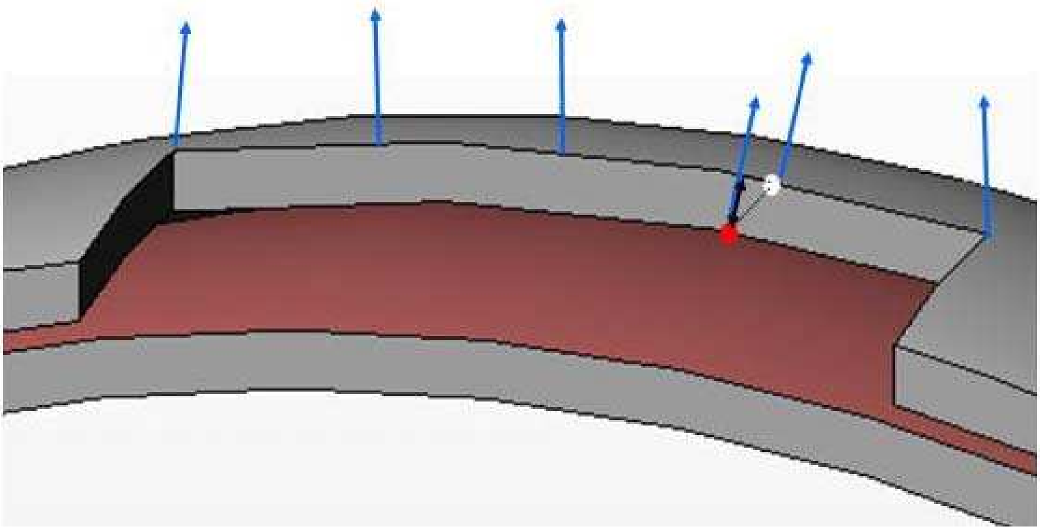


Figure 4b: Measurement of skull thickness using Method 2

3rd definition

We calculated the mean value of the 25 local normals of the outer table. This gave us an overall normal at the 25 points. At each location, thickness was defined as the distance between projections of the digitized points on this overall normal (Fig. 4c).

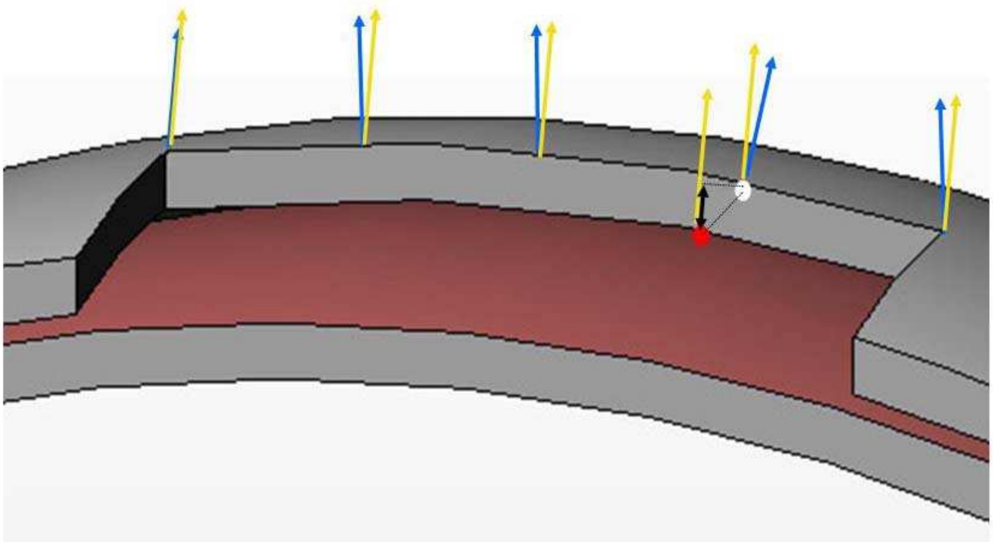


Figure 4c: Measurement of skull thickness using Method 3

4th definition

Here again, the outer surface was used for reference. We approximated this surface by using a sphere. At each point, we measured the distance between the sphere and the actual surface. We calculated the geometric mean of these MSE (Mean Square Error) distances, and the center of the sphere. At each location, thickness was defined as the difference in radius between the point and the center of the sphere.

5th definition

As in the 4th definition, we selected the sphere that best modeled the outer surface. We also calculated its MSE and its center. This center was used to calculate the other two spheres that modeled the other two layers. We calculated the MSE and radii of these two new spheres. Thicknesses were then obtained by subtracting the values of the radii.

Statistics

To determine which of the above methods was the most reliable, we evaluated the reproducibility of 30 measurements taken on the same skull by 3 investigators (10 measurements by investigator).

We obtained 150 thickness values for the same skull (5 methods x 30 measurements). As these were estimations, we considered the actual value likely approximated the mean $\overline{m}$ of the 150 values.

For each method, we evaluated its systematic error (i.e. difference between the mean values obtained with the method and $\overline{m}$) and the statistical dispersion (i.e. measurement of the dispersion around the mean values obtained with the method).

We arbitrarily decided that any measurement method with a confidence interval (CI) greater than 0.1 mm would be rejected.

We retained the measurement method for which the mean value was closest to $\overline{m}$ (lowest systematic error). The methods giving a systematic error greater than 0.2 mm were arbitrarily rejected.

In addition, we calculated the means and 95% confidence intervals (CI) for the total thicknesses and bone graft thicknesses with each of the five methods.

Results

Impact force measurement

As no significant bounce was observed at impact, it can be concluded that the whole of the energy was absorbed by the impact ($E_{absorbed\ during\ impact}$ = mgh. Mass m is expressed in kg, gravity acceleration g = 9.812m/s^2, and height h = 1 m).

The average maximum absorbable energy or impact force to failure on the intact left side was 17.7 J (SD = 6.2 J, N = 12).

The average maximum absorbable energy or impact force to failure on the donor right side was 13.86 J (SD = 3.3 J, N = 5).

In 7 cases (58%), the initial impact energy (8.0 J) produced a fracture on the donor side. Therefore, we were unable to determine the maximum absorbable energy for these 7 cases.

Thickness measurement

Results are presented in Tables 1 and 2.

	Mean value	Systematic Error	CI95
Method 1	7.4	+1.2	0.2
Method 2	6.0	-0.2	0.1
Method 3	6.4	+0.2	0.1
Method 4	5.7	-0.6	0.1
Method 5	5.6	-0.5	0.2

Mean total thickness based on the 150 calculated values is 6.2mm.

Table 1: Total thickness of parietal bone

	Mean value	Systematic Error	CI95
Method 1	3.5	+0.6	0.2
Method 2	2.7	-0.2	0.1
Method 3	2.7	-0.2	0.1
Method 4	2.8	-0.1	0.1
Method 5	2.8	-0.1	0.1

Mean thickness of parietal bone graft based on the 150 calculated values is 2.9mm.

Table 2: Thickness of parietal bone graft

The systematic error of method 1 was +0.6 mm for bone graft thickness and +1.2 mm for total thickness. The 95% CI was greater than 0.1 mm in both cases. Method 1 was rejected because it met neither of the criteria (systematic error and CI).

The systematic error of method 2 was -0.2 mm both for bone graft thickness and total thickness. The 95% CI was 0.1 mm in both cases. Method 2 was retained because it met both criteria.

The systematic error of method 3 was -0.2 mm both for bone graft thickness and +0.2 mm for total thickness. The 95% CI was 0.1 mm in both cases. Method 3 was retained because it met both criteria.

The systematic error of method 4 was -0,1mm for bone graft thickness and -0.6 mm for total thickness. The 95% CI was 0.1 mm in both cases. Method 4 was rejected because the sysematic error in total thickness measurement was far too high.

The systematic error of method 5 was -0,1mm for bone graft thickness and -0.5 mm for total thickness. The 95% CI was 0.1 mm in both cases. Method 5 was rejected because the systematic error in total thickness measurement was far too high.

Only methods 2 and 3 were retained.

We averaged these two methods to measure thicknesses.

Total thickness on the donor right side ranged from 3.0 mm to 12.4 mm with a mean of 6.2 mm (SD = 2.5 mm).

Total thickness on the intact left side ranged from 3.6 mm to 9.8 mm with a mean of 6.0 mm (SD = 1.5 mm).

Means and standard deviations were similar on both sides. The paired *t*-test confirmed that there was no significant difference ($p=0.78$) between the two sides.

Bone graft thickness ranged from 1.5 mm to 4.6 mm with a mean of 3.0 mm (SD = 0.9 mm).

Discussion

We validated a test set-up to quantify the impact resistance of parietal bone. We also designed an optoelectronic method to measure the thickness of parietal bone.

Impact force measurement

Two methods were available. The first one is the DFEA (dynamic finite element analysis) which uses a virtual skull model[11] (e.g. based on CT scan slices) or morphometric data[12-14]. For relevance, prior experiments were mandatory to validate this model. Peterson described the mechanical characteristics of the inner and outer tables[15]. Unfortunately his series was very limited (only 5 dry skulls and 5 frozen heads).

The second method consists in testing calvaria impact resistance *in vitro*. The delivered impacts were quantified to evaluate bone deformation.

Several test set-ups and mounting fixtures for evaluation of frontal bone impact resistance have been described in the literature: drop tower, electro-hydraulic piston to impact the head[16] and pendulum Charpy impact testing machine[8]. No studies about the resistance of parietal bone to mechanical impact are available in the literature.

The main disadvantage of the drop tower is the absence of a well-defined target zone, contrary to the electro-hydraulic piston.

The disadvantage of the second method is that it does not provide direct measurement of the absorbed energy. Yoganandan defined energy as the integral or the area under the force-deflection curve[16]. With the Charpy impact testing machine, a precise target zone can be defined, and calculation of the absorbed energy is very simple (E=mgh).

Our study is performed on unembalmed fresh cadaver heads. The described protocol is applicable to a virtual model. Our results can be used for validation of dynamic finite element models.

They will also be useful to validate theoretical models such as the ultrasonic method[17,13,15]. These methods use the Hooke's law which allows evaluation of the mechanical characteristics of bone based on the decrease in ultrasonic speed in the sample.

In 58% of the cases, the parietal bone on the donor side failed under the initial impact of 8 J. Therefore, the initial impact force must be decreased. We used the dichotomy principle and set the initial impact force at 4 J. We might have to bring it down to 2 J. In order to use 4 J, we had to replace the 316L stainless steel pendulum (density = 7.99) with an AU_4G aluminum pendulum (density = 2.8).

Our tests were performed on scalp free specimens. Preliminary tests had been performed on specimens with scalp coverage. These tests showed that each impact produced a permanent crush injury. After the third impact, scalp was severely comminuted, which means that beyond 3 impacts the scalp loses its shock absorbing property.

Frontal fractures are the most frequent of the cranial bone fractures. Parietal fractures are rare, and parietal fracture by a direct chock rarest. The possibilities to have a direct chock on parietal bone are to receive something on the top of the head (like a club for assault) or crack the top of the head on something getting up the ground (that was the case of the patient who crack his head on a beam).

In this preliminary study, we used cadavers whose ages ranged from 74 to 97 years, with a mean of 83 years (SD = 7 years). We understand that in general, calvarial bone grafts are performed in younger patients. Ontogenic changes in geriatric skull thickness, suture fusion (greater obliteration), decreases of elasticity and brittleness of the outer table are some of the factors which might change the distribution of the biomechanical forces following forces applies to the geriatric vault compared to the vault in younger patients

Thickness measurement

Numerous morphometric studies have been conducted to evaluate parietal bone thickness. Tellioglu used CT scan10, Moreira-Gonzalez and Jung used calipers[18,19], Lynnerup used bone biopsy[20], and Elahi used ultrasounds[21]. We could not use calipers because it required access to the inner table prior to delivering the impacts. Biopsy was not advisable because it weakened the bone. The ultrasonic method was too sensitive to probe positioning. CT scan meant three-dimensional reconstruction from two-dimensional slices whitch would have generated additional inaccuracies. Another limitation of the use of CT scan in our study is the fact of performing at least 2 CT scan per head (one for total left and right thickness and one for the thickness of outer and inner tables in the right side after parietal graft harvest). CT scan could be possible with a small number of heads but not with 12. In our future study, after validation of this protocol, we want to do more than 30 heads. It is not possible to use CT scan. The selected method required full visualization of the three surfaces to be digitized and the use of a template grid. Using a CT scan meant performing two digitizations per head (before and after bone graft harvest). Furthermore, 3-D acquisition of a grid mapped on bone surfaces is technically difficult. We then selected to use a navigation system which has the main advantage of being nondestructive and which allows the use of a calibrated perforated template grid.

Navigation systems have numerous applications in many different fields (e.g. imageless navigation). In our study, the navigation tool was used to measure parietal bone thickness. It allows to define an infinite number of measurement methods.

Using navigation systems comes closer to the intraoperative setting, than using CT scan. Therefore employing a navigation system for this study may yield on accuracy, but improves translation of the data to the actual surgery, or provides a more pragmatic approach.

Method 1 did not take account of the normal to the parietal bone surface. It did not comply with the Abbe's principle which says that parallax errors occur anytime the reference line of a measuring system does not lie along the same line as the dimension being measured. Other investigators like Tellioglu who used digital calipers[10] had to take measurements perpendicular to the parietal bone surface.

Method 2 took account of the local normal to the parietal bone surface. Therefore, the Abbe's principle was respected.

Method 3 took account of the overall normal to the parietal bone surface. The Abbe's principle was respected on the overall bone surface, but it was not strictly respected locally. The parietal bone surface is convex. Local normals were perpendicular to the convex bone surface. But the overall normal cannot be perpendicular to the surface at all points.

Therefore, owing to the convex shape of the parietal bone surface, method 2 was more appropriate.

Bone surface is irregular. Local normals took account of each irregularity, while the overall normal smoothed out these local irregularities. In this respect, method 3 was more appropriate.

We needed a method that would take account of the overall convexity of calvaria and the local irregularities of the parietal bone surface. We then averaged the thicknesses obtained with methods 2 and 3.

Methods 4 and 5 were rejected because the systematic error was too high. Still, these two methods had the advantage of allowing measurement of the curvature of the calvaria and would have allowed us to subsequently evaluate a possible correlation between the impact and the radius of curvature.

The method of measurement of parietal bone thickness that we have selected takes account of the projections in accordance with both the local and the overall normals. Local normals allow to take up the natural curve of the parietal bone. The overall normal allows to take up local irregularities. By averaging the results obtained with both methods, equal importance was given to the natural bone curve and to surface irregularities.

With this well-defined and validated test set-up, we could initiate a large cadaver study. This study will allow to accurately quantify a possible loss of impact resistance of the parietal bone following monocortical bone graft harvest from the outer table, and a possible correlation between loss of strength and thickness of the bone graft.

Conclusion

This pendulum Charpy impact testing machine allows measurement of the maximum absorbable impact force in the parietal bone region, with and without bone graft harvest, with a measurement resolution of 0.025 J. The use of an optoelectronic navigation system in association with methods 2 and 3 allows parietal bone thickness measurements which are accurate to within 0.1 mm.

Acknowledgements

This study was financially supported by Stryker compagny. Anatomy division of the University School of Medicine (Tours, France) and Pr S VELUT are gratefully acknowledged.

Conflict of interest

Laurent GEAIS was employed by Stryker Company. For the others authors there is no conflict of interest

References

1. Tessier P, Kawamoto H, Matthews D, et al. Autogenous bone grafts and bone substitutes--tools and techniques: I. A 20,000-case experience in maxillofacial and craniofacial surgery. Plast Reconstr Surg 2005;116:6S-24S; discussion 92S-94S.
2. Tessier P, Kawamoto H, Posnick J, et al. Taking calvarial grafts--tools and techniques: VI. The splitting of a parietal bone "flap". Plast Reconstr Surg 2005;116:74S-88S; discussion 92S-94S.
3. Tessier P, Kawamoto H, Posnick J, et al. Taking calvarial grafts, either split in situ or splitting of the parietal bone flap ex vivo--tools and techniques: V. A 9650-case experience in craniofacial and maxillofacial surgery. Plast Reconstr Surg 2005; 116:54S-71S; discussion 92S-94S.
4. Wolfe SA, Ghurani R, Podda S, et al. An examination of posttraumatic, postsurgical orbital deformities: conclusions drawn for improvement of primary treatment. Plast Reconstr Surg 2008; 122:1870-81.
5. Krastinova-Lolov D. Mask lift and facial aesthetic sculpturing. Plast Reconstr Surg 1995; 95:21-36.
6. Shipchandler TZ, Chung BJ, Alam DS. Saddle nose deformity reconstruction with a split calvarial bone L-shaped strut. Arch Facial Plast Surg 2008; 10:305-11.
7. Kline RM, Jr., Wolfe SA. Complications associated with the harvesting of cranial bone grafts. Plast Reconstr Surg 1995; 95:5-13; discussion 14-20.
8. Verschueren P, Delye H, Depreitere B, et al. A new test set-up for skull fracture characterisation. J Biomech 2007; 40:3389-96.

9. Yoganandan N, Pintar FA. Biomechanics of temporo-parietal skull fracture. Clin Biomech (Bristol, Avon) 2004; 19:225-39.
10. Tellioglu AT, Yilmaz S, Baydar S, et al. Computed tomographic evaluation before cranial bone harvesting to avoid unexpected hazards during aesthetic procedures. Aesthetic Plast Surg 2001; 25:198-201.
11. Kleiven S, von Holst H. Consequences of head size following trauma to the human head. J Biomech 2002; 35:153-60.
12. Camacho DL, Hopper RH, Lin GM, et al. An improved method for finite element mesh generation of geometrically complex structures with application to the skullbase. J Biomech 1997; 30:1067-70.
13. Motherway J, Doorly MC, Curtis M, et al. Head impact biomechanics simulations: A forensic tool for reconstructing head injury? Legal Medicine 2009; 11:S220-S222.
14. Willinger R, Kang HS, Diaw B. Three-dimensional human head finite-element model validation against two experimental impacts. Ann Biomed Eng 1999; 27:403-10.
15. Peterson J, Dechow PC. Material properties of the inner and outer cortical tables of the human parietal bone. Anat Rec 2002; 268:7-15.
16. Yoganandan N, Pintar FA, Sances A, Jr., et al. Biomechanics of skull fracture. J Neurotrauma 1995; 12:659-68.
17. Ashman RB, Cowin SC, Van Buskirk WC, et al. A continuous wave technique for the measurement of the elastic properties of cortical bone. J Biomech 1984; 17:349-61.
18. Moreira-Gonzalez A, Papay FE, Zins JE. Calvarial thickness and its relation to cranial bone harvest. Plast Reconstr Surg 2006; 117:1964-1971.

19. Jung YS, Kim HJ, Choi SW,et al. Regional thickness of parietal bone in Korean adults. Int J Oral Maxillofac Surg 2003; 32:638-41.
20. Lynnerup N. Cranial thickness in relation to age, sex and general body build in a Danish forensic sample. Forensic Sci Int 2001; 117:45-51.
21. Elahi MM, Watkin KL, Hakim MS, et al. A new predictive modality of cranial bone thickness. Ann Plast Surg 1999; 42:651-57.

Dans cette première partie du travail, nous avons validé un modèle permettant de tester la résistance du crane humain au choc après un prélèvement pariétal monocortical.

Nous avons pu aussi valider un modèle de mesure avec un système de navigation chirurgicale optoélectronique de l'épaisseur du crane avec une précision de 0.1 mm.

Ce travail a fait l'objet d'une publication acceptée dans la revue américaine *Journal of Craniofacial Surgery* (IF = 0.812)

Nous avons alors réalisé la deuxième partie de l'étude au Laboratoire d'Anatomie de la Faculté de Médecine de Tours sur 30 têtes fraîches, non congelées de cadavres humains.

L'objectif principal de cette deuxième partie de l'étude était de quantifier la perte de résistance après prélèvement d'un greffon pariétal monocortical. L'objectif secondaire était d'établir une corrélation entre la résistance du crâne et son épaisseur.

La quantification de la perte de résistance était réalisée en comparant le choc maximal supportable avant fracture du côté prélevé avec le côté non prélevé

En moyenne, la perte de résistance de la zone prélevée était de 36% ($p=1.10^{-10}$). La diminution de l'épaisseur correspondante était de 40%. La corrélation entre les deux paramètres était modérée ($R=0.46$) mais hautement significative ($p<0,0001$).

Ce travail a été accepté pour publication dans la revue américaine *Plastic and Reconstructive Surgery* (IF = 2.743)

Deuxième partie :

Résistance du crâne après prélèvement pariétal

Résumé

Introduction :

Le prélèvement pariétal est fréquemment utilisé en chirurgie craniomaxillofaciale. L'objectif principal de notre étude était de quantifier la perte de résistance après prélèvement d'un greffon pariétal monocortical. L'objectif secondaire était d'établir une corrélation entre la résistance du crâne et son épaisseur.

Matériel et Méthodes : L'étude a été menée sur 30 têtes fraîches humaines non congelées et pleines. La quantification de la perte de résistance était réalisée en comparant le choc maximal supportable avant fracture du côté prélevé avec le côté non prélevé. Nous avons utilisé un mouton-pendule de Charpy préalablement calibré.

Les mesures des épaisseurs ont été réalisées grâce à un système de navigation chirurgicale optoélectronique.

Resultats : la perte de résistance de la zone prélevée est de 36% ($p=1.10^{-10}$). La diminution de l'épaisseur correspondante est de 40%. La corrélation entre les deux paramètre est modérée ($R=0.46$) mais hautement significative ($p<0,0001$)

Conclusion : La perte de résistance du crâne est significative. Cependant, les complications graves au niveau de site de prélèvement sont rares. La pression juridique conduit le chirurgien à mesurer pour chacun de ses actes le risque encouru par le patient et le bénéfice attendu, qu'ils soient immédiats ou retardés. Cette étude montre que les risques ne sont pas négligeables. Il est donc important d'en informer le patient.

Evaluation of skull strength following parietal bone graft harvest

Key words: parietal bone, donor site, thickness, calvaria, skull

Boris LAURE, MD (a,b), François TRANQUART, MD, PhD (b), Laurent GEAIS (a), Dominique GOGA, MD(a)

(a) Service de Chirurgie Maxillo-faciale et Plastique de la Face, Université François Rabelais, Hôpital Trousseau CHRU Tours, 37044 Tours cedex, France

(b)Unité Médicale Ultrasons INSERM U930-CNRS 2448 Université François Rabelais Hôpital Bretonneau CHRU Tours- 37044 Tours Cedex, France

Corresponding author contact:

Dr Boris LAURE (MD)

Service de Chirurgie Maxillo-faciale et Plastique de la Face, Université François Rabelais, Hôpital Trousseau CHRU Tours, 37044 Tours cedex, France

Mail: laure@med.univ-tours.fr

Phone: +33 247 474 640

Sources of funds supporting the work and a statement of financial interest

This study was supported by Stryker Company.

There was no financial interest for the authors.

Laurent GEAIS is employed by Stryker Company.

Abstract

Background:

Parietal bone grafts are commonly used in craniomaxillofacial surgery. The primary aim of our study was to quantify the loss of strength following monocortical parietal bone graft harvest. The secondary aim was to establish a correlation between strength and thickness of calvaria.

Methods:

Thirty fresh human cadaver heads (non-frozen, unembalmed heads) were used for this study. Loss of strength was determined by comparing the maximum impact resistance of bone on the donor side vs the intact side, using a pre-calibrated pendulum Charpy impact testing machine.

Thickness was measured using a surgical navigation system with optoelectronic tracking.

Results:

Loss of strength at the donor site was 36% ($p=10^{-10}$) for 40% loss of thickness. Although correlation between these two parameters is rather moderate ($r=0.46$), it is highly significant ($p<10^{-4}$).

Conclusions:

Although loss of strength is quite significant, serious complications at the donor site are rare. As shown in this study, these risks are non-negligible. However, due to the strong legal pressure, surgeons must carefully weigh the risks incurred by the patient against the expected benefits, whether immediate or deferred. Therefore, the patient should receive well-documented information before such monocortical parietal bone graft harvest.

Introduction

Autologous bone grafts obtained from the outer table of the parietal bone are commonly used for craniofacial reconstruction[1-2]. Membranous bone undergoes less resorption than enchondral bone[3]. This is why it is preferred in several indications including: pre-implant procedures[4], orbital surgery[5], facial deformities or facial cosmetic surgery[6-7]. Removing bone from the outer table decreases thickness of the calvaria. Therefore, it might potentially affect impact resistance at the donor site and create a weak area which might lead to deleterious complications[8]. Serious complications at the donor site are rare[8-11]. However, due to strong legal pressure, surgeons carefully weigh the risks incurred by the patient against the expected benefits (whether immediate or deferred), particularly for non-vital surgery.

The impact resistance of parietal bone after bone graft harvest has never been carefully evaluated. Several types of set-ups and tests have been used to evaluate the impact resistance of calvaria under different conditions: free fall, electro-hydraulic piston[12], and Charpy impact test using a swinging pendulum[13]. In this study, we used a pre-calibrated pendulum Charpy impact testing machine.

The primary aim of this study was to quantify the loss of strength following monocortical parietal bone graft harvest. Loss of strength was determined by comparing the maximum impact resistance of bone on the donor side vs the intact side. The secondary aim was to establish a correlation between strength and thickness of calvaria.

Materials and Methods

Fresh human cadaver heads

Thirty fresh human cadaver heads (non-frozen, unembalmed heads) were used for this study which was conducted at the Laboratory of the University School of Medicine (Tours, France) in compliance with ethical rules as regards human experimentations on people who have donated their body to science. All adult specimens were free from calvarial injuries or bone diseases.

The series included 11 males (37%) and 19 females (63%).

Age at death ranged from 60 to 97 years, with a mean of 81 years (SD = 8 years).

All tests were performed between 4 and 31 days after the death with a mean of 11 days (SD = 7 days).

Specimen Preparation

The entire scalp was removed and the calvaria was exposed after elevation of periosteum. Landmarks for bone graft harvest on the right side were: 10 mm posterior to the coronal suture and 20 mm lateral to the sagittal suture[1]. The harvest area measured 40 mm x 40 mm (1600 mm^2) (Fig.1)

Parietal bone thickness was measured using an interactive surgical navigation system with optoelectronic tracking (Stryker Cart 1, Pusignan, France). Thickness of the outer table was measured at 25 points. Thickness of the inner table was measured at 16 points.

A rigid marker was fixed in the right cheekbone using a 3.2 mm diameter threaded pin. A tracker was mounted onto the pin (Fig. 1). Point digitization was performed with the use of a pointer (by touching the pointer tip to the selected point) (Fig. 2).

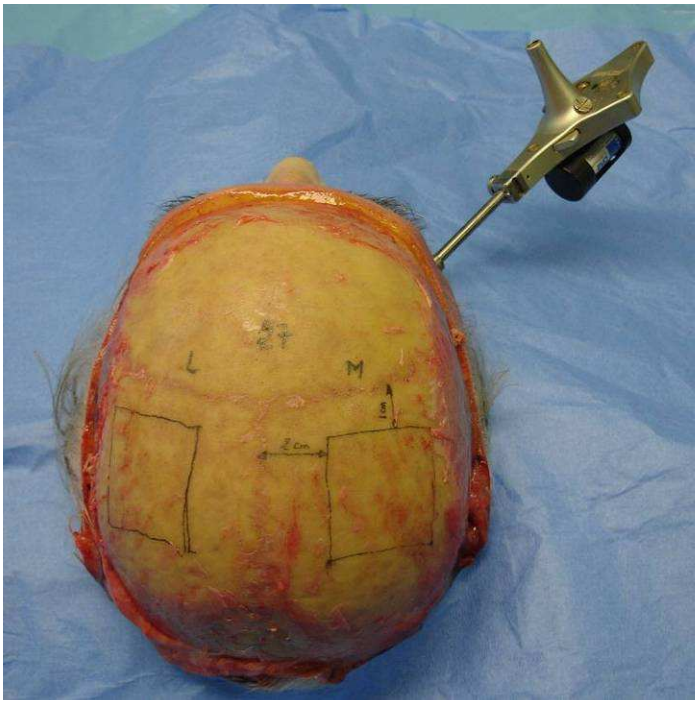


Fig. 1: Right and left parietal bone areas – Tracker

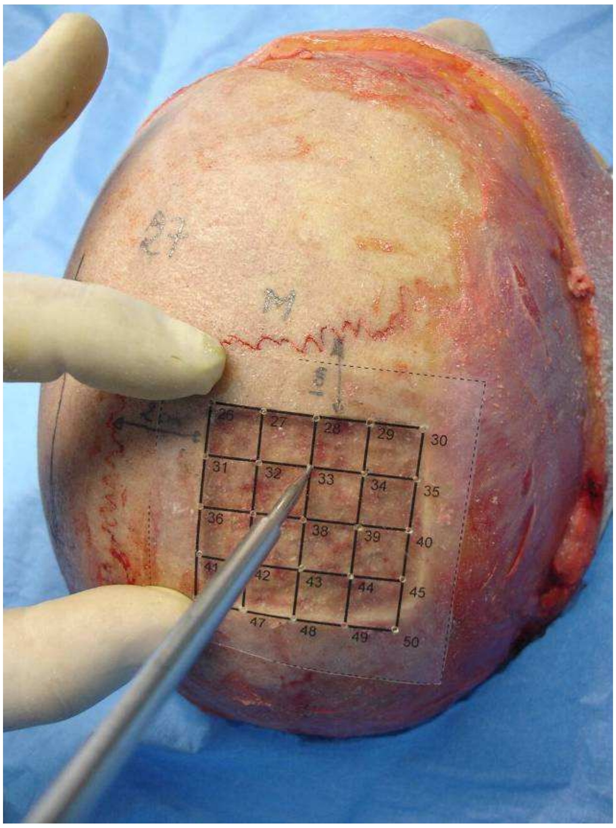


Fig. 2: Point digitization after bone graft harvest

Position of the pointer relative to the tracker was recorded by the camera and evaluated by the software.

The digitization procedure was repeated three times running.

The first time, 25 points were digitized through a clear perforated template grid numbered from 1 to 25 at intervals of 10 mm. A monocortical graft was then taken from the parietal bone. The outer table was reamed down to the diploe using a round burr. The parietal bone flap was then split with sharp bone splitters using the Tessier technique[1].

The second time, another 25 points were digitized through a clear perforated template grid numbered from 26 to 51 at intervals of 10 mm (Fig. 2). The thickness of the harvested bone graft was measured based on the distances between these points.

After the impact, the inner table was cut out using a milling machine. A third digitization was then performed through a clear perforated template grid numbered from 52 to 67 at intervals of 10 mm. The pointer tip was applied to the lowest point at the perimeter of the area.

Mean total thickness was calculated based on the 16 perimeter point's difference collected during the first and third digitization procedures. Mean thickness of the bone graft was calculated based on the 25 points difference collected during the first and second digitization procedures (Fig. 3).

Due to the irregular and curved surfaces of the inner and outer tables, during a preliminary study, we had compared several measurement methods and developed a formula that takes account of the calvaria curvature and the surface irregularities.

We averaged two of these methods to measure thickness.

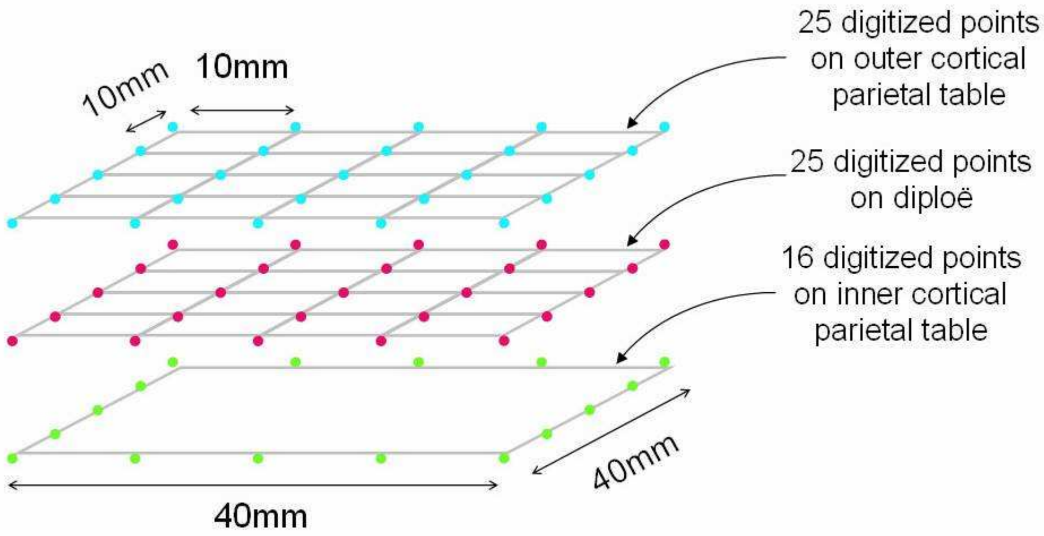


Fig. 3: Digitized points for calculation of thickness

The systematic error of the first method was 0.2 mm both for bone graft thickness and total thickness. The 95% CI was 0.1 mm in both cases. The systematic error of the second method was 0.2 mm for bone graft thickness and 0.2 mm for total thickness. The 95% CI was 0.1 mm in both cases.

We also measured the radius of curvature of this parietal area. The radius of curvature of the outer table was calculated based on the 25 points of the first digitization procedure, that of the inner table on the 25 points of the second digitization procedure.

Measurement of absorbed energy

Impact intensity was derived from the energy absorbed by the skull.

We developed a pendulum Charpy impact testing machine in which the hammer was released from a height of one meter (Fig. 4) and stroke the target zone at a speed of 9.812 m/s^2 (i.e. under normal acceleration due to gravity). The energy absorbed by the impact was calculated by comparing the potential energy at the beginning and at the end of the test. The whole of the kinetic energy was absorbed by the skull. No bounce was noted when fracture occurred. At the beginning of the test, the swinging pendulum was in a horizontal position (checked with a spirit level). Therefore, the height of drop was one meter. In order to eliminate the energy generated by friction, self-aligning ball bearings were used to guide the axis of the pendulum.

Each specimen was firmly held in a vice in a slanted position so that the hammer surface was parallel to the bone surface.

The rigid fixation provided by the vice and the secure connection of all component parts of the mounting eliminated the risk of energy loss.

$$E_{\text{absorbed during impact}} = mgh$$

m = mass in kg

g = 9.812 m/s^2

h = 1 m

The parietal target zone was a square of side length 40 mm. To fit this area, we used a 28.7 mm diameter (surface of a square inch = 645 mm^2) hammer similar to that used by Yoganandan[14].

Fig. 4: Test Set-up

Loads were gradually increased until failure (bone fracture) (Fig. 5). A fracture was defined by a visual linear crack or depressed skull fracture.

We counted the number of impacts on each side before failure.

We had validated this test set-up and defined the minimum impact force (4 joules) during a preliminary study on 12 skulls.

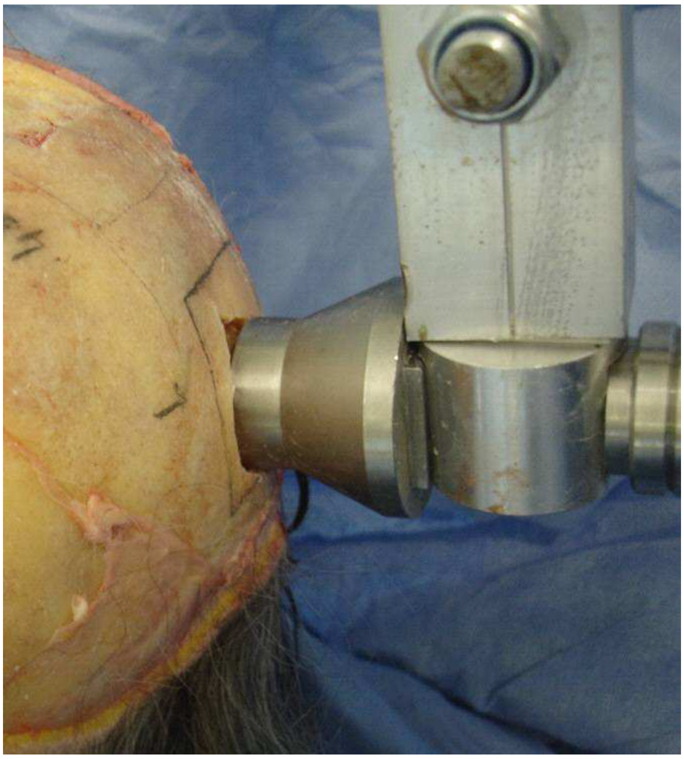


Fig. 5: Impact on parietal bone

Statistical method

We used the F test to analyze variance in thickness of the right and left sides.

A paired *t*-test was used for statistical analysis of the difference in parietal bone thickness between the right and left sides. A paired *t*-test was also used for statistical analysis of impact resistance on donor right side versus intact left side (left side was used as control).

A *t*-test was used for the statistical analysis of chocks' numbers on right and left sides.

A Pearson test was used to evaluate the correlation between thickness and strength of the parietal bone.

Male and female populations were segmented and a *t*-test was used to evaluate the influence of the gender parameter.

Results

Thickness

Thickness data are presented in Table 1.

Thickness measurements in 30 cadaver heads

	Total thickness	Total thickness	Residual thickness after harvest	Decrease in thickness	Total thickness
Min	3.1 mm	4.2 mm	1.8 mm	14%	-4.6 mm
Max	10.0 mm	10.5 mm	6.4 mm	74%	+4.4 mm
Mean	5.9 mm	6.6 mm	4.0 mm	**40%*(1)**	**+0.8 mm*(2)**
CI95	0.57 mm	0.48 mm	0.43 mm	4%	0.2 mm

***(1)** $p=8.10^{-11}$

***(2)** $p=10^{-4}$

Table 1: Thickness measurements in 30 cadaver heads

Total thickness was measured on both sides (60 measurements). Values ranged from 3.1 mm to 10.5 mm with a mean of 6.4 mm (SD = 1.8 mm). Total thickness on donor right side ranged from 4.2 mm to 10.5 mm with a mean of 6.6 mm (SD = 1.3 mm). Total thickness on intact left side ranged from 3.1 mm to 10 mm with a mean of 5.9 mm (SD = 1.6 mm). In our series, total thickness on right side was significantly greater than on left side ($p=3.10^{-4}$). Thickness of bone graft ranged from 1 mm to 5.2 mm with a mean of 2.6 mm (SD = 0.8 mm).

The ratio between bone graft thickness and total thickness of parietal bone ranged from 14% to 74% with a mean of 40% (SD = 12%). Loss of thickness at donor site was highly significant ($p=8.10^{-11}$).

Radius of curvature of the outer table ranged from 93.2 mm to 97.5 mm with a mean of 96.5 mm (SD = 0.78 mm). Radius of curvature of the inner table ranged from 93.1 mm to 96.9 mm with a mean of 95.1 mm (SD = 0.88 mm). Radius of curvature of the inner table was significantly smaller than that of the outer table ($p=10^{-13}$).

Energy

Results are presented in Table 2 and illustrated in Fig. 6.

Energy required to break the parietal bone targets in the 30 cadaver heads

	Intact Left side (control)	Right side after harvest	Loss of strength after harvest (right vs left)
Min	5.6 J	4.2 J	5%
Max	19.8 J	15.7 J	65%
Mean	11.4 J	7.2 J	**36%***
SD	3.8 J	2.9 J	15%

*$p=10^{-10}$

SD: Standard Deviation

Table 2: Energy required to break the parietal bone targets in the 30 cadaver heads

The crack in the right donor site was depressed in all 30 heads (100%). On the left side, the crack was linear in 11 cases (37%) and depressed in 19 cases (63%).

The maximum absorbable energy or impact force to failure on the donor side ranged from 4.2 J (i.e. 0.431 kg falling from 1 m height) to 15.7 J (i.e. 1631 g falling from 1 m height) with a mean of 7.2 J (i.e. 0.749 kg falling from 1 m height) (SD = 2.9 J).

On the intact left side, values ranged from 5.6 J (i.e. 0.581 kg falling from 1 m height) to 19.8 J (i.e. 2.059 kg falling from 1 m height) with a mean of 11.4 J (i.e. 1.189 kg falling from 1 m height) (SD = 5.1 J).

The mean chocks' number was 5.8 on the harvested right side, and 7.8 on the control left side. The chocks' number was statistically higher on the control side (p=0.018).

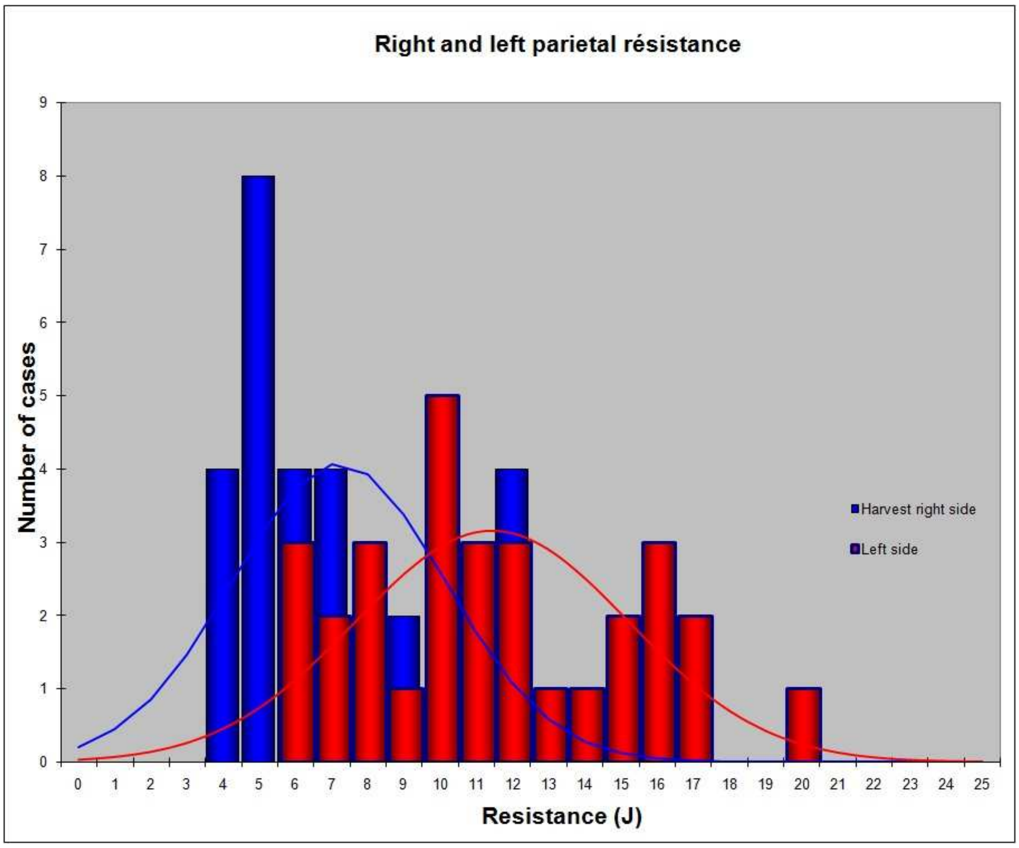


Fig. 6: Impact resistance after bone graft harvest

Loss of strength

Results are presented in Table 2.

The difference in strength between the intact left side and the donor right side ranged from 5% to 65% with a mean of 36% (SD = 15%). Loss of strength at donor site was highly significant ($p=1.10^{-10}$).

Correlation between strength and thickness of parietal bone

The secondary aim of this study was to establish a correlation between strength and thickness of the skull.

The Pearson correlation coefficient calculated based on the 60 data collected on the right and left sides was significant: 0.464, $p<10^{-4}$ (Fig. 7).

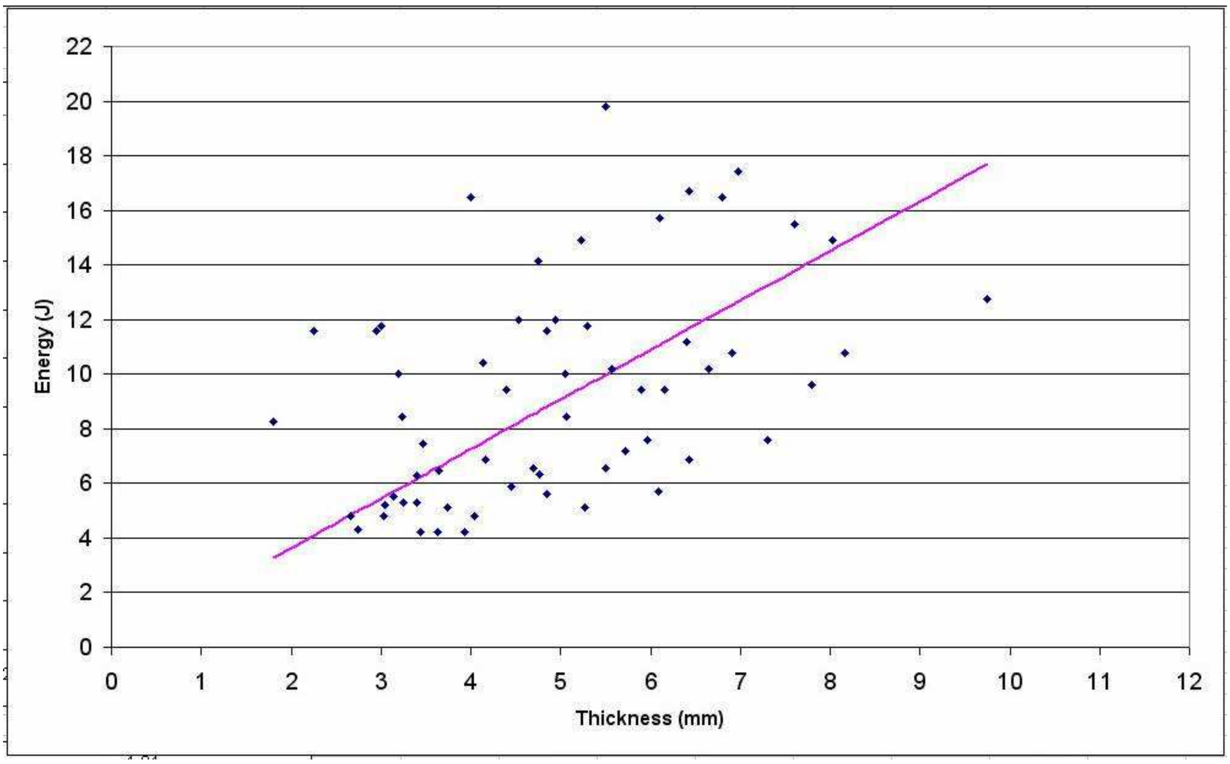


Fig. 7: Evaluation of correlation between strength and thickness of parietal bone

(Linear correlation coefficient: r=0.46; p<0.0001)

Influence of gender parameter

Total mean thickness (22 impacts) in males was 4.7 mm. Total mean thickness (38 impacts) in females was 5.0 mm. The mean difference of 5.6% between these two populations was not statistically significant (p=0.54) (*t*-test).

Total mean impact resistance (22 impacts) in males was 7.5 J. Total mean impact resistance (38 impacts) in females was 10.4 J. The mean difference of 28% between these two populations was statistically significant (p=0.005) (*t*-test).

Discussion

This study shows that removal of a 40 mm x 40 mm monocortical parietal bone graft results in 36% decrease in bone strength as compared to the intact contralateral side. Furthermore, the Pearson test showed a correlation between impact resistance and thickness of parietal bone ($p=10^{-4}$).

Decrease in parietal bone strength (36%)

Bone removal results in a mean loss of strength of 36%. In our series, loss of strength was highly significant ($p=1.10^{-10}$). Total thickness of the donor right side before harvesting was significantly greater than on the intact left side. The mean difference between right and left sides was 0.8 mm (SD = 1.5 mm, $p=3.10^{-4}$), and the chocks' number was statistically higher on the control side (p=0.018). These two last arguments make our results even more meaningful. In other studies[15-17] on parietal bone, no significant difference in thickness has been found between the right and left sides. Moreira reported a mean parietal bone thickness of 6.32 mm in 281 dry skulls[16]. In Sullivan's necropsy study[18] involving 37 patients, parietal bone thickness was 6.4 mm.

In our study, total mean parietal bone thickness measured (60 measurements) in 30 fresh cadaver heads was 6.4 mm.

Influence of gender on parietal bone thickness was not statistically significant, which is consistent with the results published by Lynnerup[19]. However, it should be noted that impact resistance of parietal bone is much higher in females than in males (28% difference, p=0.005).

In our study we used cadavers whose ages ranged from 60 to 97 years of age, with a mean of 81 years (SD = 8 years). We understand that in general, calvarial bone grafts are performed in younger patients. Ontogenic changes in geriatric skull thickness (i.e., decreasing thickness[20] or not[21]) suture fusion (greater obliteration), decreases of elasticity and brittleness of the outer table are some of the factors which might change the distribution of the biomechanical forces following forces applies to the geriatric vault compared to the vault in younger patients.

Consequences of decreased bone strength

The main intraoperative risk is penetration of the inner table (10-11% according to Wolfe, 15% according to Fearon)[8,22]. For a well trained and experienced surgeon, it is a rare event. Serious complications have been reported however, including superior sagittal sinus laceration[9] and intracerebral hematoma[11].

Potential postoperative consequences of decrease in parietal bone strength are not well known, but one can say for sure that the donor site is more prone to fracture if impacted. A fracture or a depressed skull fracture may cause severe extradural or subdural damage of varying degree. In particular, hematomas may be associated with severe sequelae[8]. In children, Wolfe recommends repositioning the outer table after harvesting. In professional football players, he recommends selecting another donor site if the graft exceeds half the total thickness of the parietal bone.

In another retrospective study, Wolfe[8] reported an overall complication rate of 0.18%. Keen[23] suggested a local complication rate of 3-5% and 1% of neurologic complications.

Late postoperative complications have never been reported. Nevertheless, we performed this study as a result of our knowledge of a patient who, following a calvarial bone graft, died after sustaining a traumatic injury to his skull. His death was caused by an extra dural hematoma. The autopsy revealed a fracture of the calvaria on the site of the cranial bone harvest. This case has never been reported in a medical journal.

Even though the complication rate is so low that, even today, very few surgeons inform their patients of the decrease in skull strength after surgery, the results provided in the present study clearly support the need that our patients must be aware of this risk.

Correlation between strength and thickness

According to our findings, harvesting of a parietal bone graft results in 40% decrease in bone thickness and 36% decrease in bone strength. Study of the correlation between impact resistance and bone thickness supports these findings. Although moderate ($r=0.46$), the statistically significant positive correlation (Pearson test, $p=10^{-4}$) validates the fact that the thicker the parietal bone, the higher its impact resistance. In our case $r^2 = 0.23$ (r^2 values give the percentage of variation explained by the regression equation). Only 23% of skull strength is explained by skull thickness.

Other possible factors contributing to skull strength that could account for the other 77% of the variation include age, cadaveric vs living tissue, timing of suture fusion….In our study, the radius of curvature of the outer table was significantly greater than that of the inner table ($p=10^{-13}$). If added to the mild difference between decreased thickness and loss of strength (4%), this finding suggests that the inner table may be stronger than the outer table.

Future prospects of this study

We routinely use parietal bone grafts which are indispensable in craniofacial surgery. The aim of our study was not to restrict their use but to stress the fact that bone removal results in 36% decrease in strength at donor site.

In addition to biomechanical considerations, it must be pointed out that after harvest, the donor site shows a slight depression that is unsightly in patients with short hair; it may even cause distress in some patients.

Even reconstruction of the donor site with biomaterials is not systematic. It could make patients more comfortable after surgery. At issue is still the question of whether such a reconstruction would have the biomechanical capacity to restore the initial bone strength?

Acknowledgements

This study was financially supported by Stryker Company. Anatomy division of the University School of Medicine (Tours, France) and Pr S VELUT are gratefully acknowledged.

References

1. Tessier P, Kawamoto H, Posnick J, Raulo Y, Tulasne JF, Wolfe SA. Taking calvarial grafts--tools and techniques: VI. The splitting of a parietal bone "flap". *Plast Reconstr Surg*. 2005; 116:74S-88S; discussion 92S-4S.

2. Tessier P, Kawamoto H, Posnick J, Raulo Y, Tulasne JF, Wolfe SA. Taking calvarial grafts, either split in situ or splitting of the parietal bone flap ex vivo--tools and techniques: V. A 9650-case experience in craniofacial and maxillofacial surgery. *Plast Reconstr Surg*.2005;116:54S-71S; discussion 92S-4S.

3. Zins JE, Whitaker LA. Membranous versus endochondral bone: implications for craniofacial reconstruction. *Plast Reconstr Surg*.1983;72:778-85.

4. Le Lorc'h-Bukiet I, Tulasne JF, Llorens A, Lesclous P. Parietal bone as graft material for maxillary sinus floor elevation: structure and remodeling of the donor and of recipient sites. *Clin Oral Implants Res.* 2005; 16:244-9.

5. Wolfe SA, Ghurani R, Podda S, Ward J. An examination of posttraumatic, postsurgical orbital deformities: conclusions drawn for improvement of primary treatment. *Plast Reconstr Surg*.2008; 122:1870-81.

6. Krastinova-Lolov D. Mask lift and facial aesthetic sculpturing. *Plast Reconstr Surg*. 1995;95:21-36.

7. Shipchandler TZ, Chung BJ, Alam DS. Saddle nose deformity reconstruction with a split calvarial bone L-shaped strut. *Arch Facial Plast Surg.* 2008; 10:305-11.

8. Kline RM, Jr., Wolfe SA. Complications associated with the harvesting of cranial bone grafts. *Plast Reconstr Surg*.1995; 95:5-13; discussion 4-20.

9. Cannella DM, Hopkins LN. Superior sagittal sinus laceration complicating an autogenous calvarial bone graft harvest: report of a case. *J Oral Maxillofac Surg*.1990; 48:741-3.

10. Wilkinson HA. Autogeneic skull bone graft . *Neurosurgery*.1987;21:760.

11. Young VL, Schuster RH, Harris LW. Intracerebral hematoma complicating split calvarial bone-graft harvesting. *Plast Reconstr Surg*. 1990; 86:763-5.

12. Yoganandan N, Pintar FA, Sances A, Jr., Walsh PR, Ewing CL, Thomas DJ, et al. Biomechanics of skull fracture. *J Neurotrauma*. 1995; 12:659-68.

13. Verschueren P, Delye H, Depreitere B, Van Lierde C, Haex B, Berckmans D, et al. A new test set-up for skull fracture characterisation. *J Biomech*. 2007; 40:3389-96.

14. Yoganandan N, Pintar FA. Biomechanics of temporo-parietal skull fracture. *Clin Biomech (Bristol, Avon).* 2004; 19:225-39.

15. Jung YS, Kim HJ, Choi SW, Kang JW, Cha IH. Regional thickness of parietal bone in Korean adults. *Int J Oral Maxillofac Surg*. 2003; 32:638-41.

16. Moreira-Gonzalez A, Papay FE, Zins JE. Calvarial thickness and its relation to cranial bone harvest. *Plast Reconstr Surg*. 2006; 117:1964-71.

17. Tellioglu AT, Yilmaz S, Baydar S, Tekdemir I, Elhan AH. Computed tomographic evaluation before cranial bone harvesting to avoid unexpected hazards during aesthetic procedures. *Aesthetic Plast Surg.* 2001; 25:198-201.

18. Sullivan WG, Smith AA. The split calvarial graft donor site in the elderly: a study in cadavers. *Plast Reconstr Surg*.1989; 84:29-31.

19. Lynnerup N. Cranial thickness in relation to age, sex and general body build in a Danish forensic sample. *Forensic Sci Int*. 2001; 117:45-51.

20. Sullivan WG, Smith AA. The split calvarial graft donor site in the elderly: a study in cadavers. *Plast Reconstr Surg.* 1989 ;84:29-31.

21. Hwang K, Hollinger JO, Chung RS, Lee SI. Histomorphometry of parietal bones versus age and race. *J Craniofac Surg.* 2000;11:17-23.

22. Fearon JA. A magnetic resonance imaging investigation of potential subclinical complications after in situ cranial bone graft harvest. *Plast Reconstr Surg*.2000 ;105:1935-9.

23. Keen M. Complications of harvesting cranial bone grafts. *Plast Reconstr Surg*.1995;96:1753.

Nous avons montré dans cette deuxième partie qu'en moyenne, la perte de résistance de la zone pariétale prélevée était de 36% ($p=1.10^{-10}$). La diminution de l'épaisseur correspondante était de 40%. La corrélation entre les deux paramètres était modérée ($R=0.46$) mais hautement significative ($p<0,0001$).

Notre étude est l'une des rares réalisée sur têtes de cadavres fraîches pleines. Le protocole décrit peut être reproduit virtuellement. Nos résultats peuvent servir pour la validation de modèles d'éléments finis dynamiques (DFEA).

Nous utilisons de façon courante le prélèvement pariétal. Ce prélèvement est indispensable en chirurgie craniofaciale. Le but de l'étude n'est pas de limiter l'utilisation de ce type de prélèvement mais de prendre conscience que la résistance du crâne est diminuée de 36% du côté prélevé.

En dehors de ces considérations biomécaniques, le prélèvement crânien laisse une dépression osseuse en regard pouvant être source de gène esthétique chez les patients avec des cheveux courts ou d'angoisse chez certains (Fig.7).

Fig.7:Séquelle de prélèvement pariétal droit

La reconstruction du site de prélèvement par biomatériau n'est pas systématique, mais elle pourrait combler l'inconfort engendré par la dépression. Cependant demeure la question de son efficacité en terme biomécanique. Cette reconstruction peut-elle permettre de retrouver une résistance du crâne similaire à celle du crâne initial ?

Pour des raisons éthiques évidentes, cette étude ne peut pas être réalisée chez l'humain. Nous avons donc évalué la résistance du crane chez le mouton après un prélèvement crânien monocortical. Cette étude a été réalisée à l'Institut National de Recherche Agronomique de Nouzilly (37380). Elle est développée dans la troisième partie de cette thèse. Cet article est soumis dans la revue européenne *Journal of Cranio-maxillo-facial Surgery* (IF= 1.38)

Troisième partie :

Résistance du crâne du mouton après prélèvement monocortical de voûte crânienne

Résumé

Introduction

Les greffes osseuses pariétales sont utilisées en chirurgie craniofaciale. Ce prélèvement diminue l'épaisseur de la voûte et entraîne probablement une perte de résistance. Celle-ci n'a jamais été quantifiée et aucune complication n'y a été associée. La reconstruction du site de prélèvement se développe mais on ne connaît pas son efficacité sur la résistance.

Le but de notre étude est de quantifier la perte de résistance due à un greffon crânien monocortical chez le mouton.

Les valeurs obtenues nous permettront d'évaluer dans un second temps l'efficacité de la reconstruction du site de prélèvement en terme de résistance au choc.

Matériel et Méthodes

L'étude a été menée sur 34 têtes fraîches de cadavres de brebis, non congelées et pleines.

Nous avons réalisé un prélèvement monocortical à la partie postérieure de l'os frontal droit.

Nous avons utilisé un système de navigation optoélectronique actif pour la mesure des épaisseurs.

L'intensité du choc était mesurée par l'énergie absorbée par le crâne grâce à un mouton-pendule de Charpy. Le percuteur venait taper dans la zone frontale cible définie. Les masses ont été augmentées progressivement jusqu'à la fracture de l'os

Résultats

L'épaisseur totale mesurée sur les deux côtés variait de 3mm à 10mm avec une moyenne de 6mm et un écart type de 1,4mm.

La différence de résistance entre le côté gauche non prélevé et le côté droit prélevé variait en moyenne de 49% et un écart type de 17%.

La perte de résistance due au prélèvement frontal était très significative ($p=6.10^{-10}$ au test de Student).

Conclusion

Nous avons montré dans cette étude la diminution de résistance du crâne du côté prélevé. La reconstruction par biomatériau du site de prélèvement permet de diminuer les séquelles esthétiques liées à la dépression mais on ne connaît actuellement pas son efficacité sur la résistance. Ce type d'étude n'est pas réalisable chez l'homme pour des raisons éthiques évidentes.

Ces données vont nous permettre de réaliser une étude chez le mouton, pour comparer la résistance de la zone frontale prélevée, et reconstruite avec un ciment d'hydroxyapatite.

Resistance of the sheep skull after a monocortical cranial graft harvest

Boris LAURE, MD (a,b), Anaïs PETRAUD (a), Florent SURY (a), François TRANQUART, MD, PhD (b), Dominique GOGA, MD (a)

(a) Service de Chirurgie Maxillo-faciale et Plastique de la Face, Université François Rabelais, Hôpital Trousseau CHRU Tours, 37044 Tours cedex, France

(b)Unité Médicale Ultrasons INSERM U930-CNRS 2448 Université François Rabelais Hôpital Bretonneau CHRU Tours- 37044 Tours Cedex, France

Key words: parietal bone, donor site, thickness, calvaria, skull, biomechanics

Short title: Sheep skull resistance

Corresponding author contact:

Dr Boris LAURE (MD)

Service de Chirurgie Maxillo-faciale et Plastique de la Face, Université François Rabelais, Hôpital Trousseau CHRU Tours, 37044 Tours cedex, France

Mail: laure@med.univ-tours.fr

Phone: +33 247 474 640

Summary

Introduction

Cranial bone grafts are commonly used for preimplant or facial reconstructive surgery. However, removing bone may weaken the parietal bone and lead to a loss of resistance. This loss has never been quantified. The harvest site reconstruction is increasing but its effectiveness on the resistance is unknown.

The aim of our study is to quantify the loss of resistance due to a monocortical cranial bone graft harvest in sheep.

Materials and Methods

Thirty four fresh sheep cadaver heads were used for the study. We performed a monocortical bone graft harvest on the posterior part of the right frontal bone. We used a surgical navigation system with optoelectronic tracking to measure bone thickness.

To evaluate chock resistance, we developed a pendulum Charpy impact testing machine. The impact force hit the defined target frontal area.

Results

The total thickness on both sides ranged from 3 mm to 10 mm with a mean of 6 mm (SD = 1.4mm).

The loss of resistance between the intact left side and the harvested right side varied with a mean of 49% (SD = 17%) and was very significant ($p=6.10^{-10}$).

Conclusion

We stated in this study the skull loss of resistance on the harvested side. Reconstruction using biomaterials of the harvested site allows the reduction of aesthetic relapses due to the depression but we do not know yet its effectiveness on resistance. This kind of study can't be performed in humans for some obvious ethical reasons.

These data will allow us to carry out a study in sheep to evaluate the harvested frontal area resistance, reconstructed with hydroxyapatite cement.

Introduction

Autologous cranial bone grafts harvested from the outer table of the parietal bone are commonly used in preimplant surgery for augmentation of the alveolar ridge [1-3], sinus floor elevation [4, 5] and for other cranio-maxillo-facial reconstructions [6-9] Removing bone from the parietal area decreases the thickness of the calvaria and may potentially affect impact resistance of the donor site. Despite the frequency of these removals, this loss of resistance has never been quantified. Only preoperative complications have been reported [10-13].

Out of biomechanical considerations, it must be pointed out that after harvest, the donor site shows a slight depression that is unsightly in patients with short hair. It may even cause distress in some patients. The reconstruction of the donor site is sometime performed with biomaterials (methylmethacrylate [14], hydroxyapatite cement [15]). It could make patients more comfortable after surgery. At issue is still the question of whether such a reconstruction would have the biomechanical capacity to restore the initial bone strength?

The aim of our study was to quantify the loss of resistance due to monocortical cranial graft harvest in sheep and to test the correlation between the resistance and the skull thickness.

In a second step, the results of this study will allow to evaluate the effectiveness of the harvested site reconstruction in terms of impact resistance.

Material and Methods

Animal heads

Thirty four Ile-de-France sheep fresh cadaver heads (unfrozen and full) were used for the study. The experimental design was made in a conventional structure (INRA, Nouzilly, 37380, France).

All tests were performed between 2 and 6 days after the death with a mean of 5 days (SD=1.4 days).

Surgical techniques

The entire scalp was removed and the skull was exposed after elevation of periosteum.

The posterior part of the frontal bones were used because they are pair and symmetric.

Landmarks for bone graft harvest on the right side were: 5 mm anterior to the coronal suture (between parietal and frontal bone) and 5 mm lateral to the sagittal suture (between both frontal bones). The right frontal harvest area measured 25 mm x 25 mm (625 mm²) (Fig.1). Frontal bone thickness was measured using an interactive surgical navigation system with optoelectronic tracking (Stryker Cart 1, Pusignan, France). A rigid and stable marking was fixed in the right maxillary bone using a threaded navigation pin (locked, diameter 3.2mm). A tracker was fixed on this pin (Fig.1).

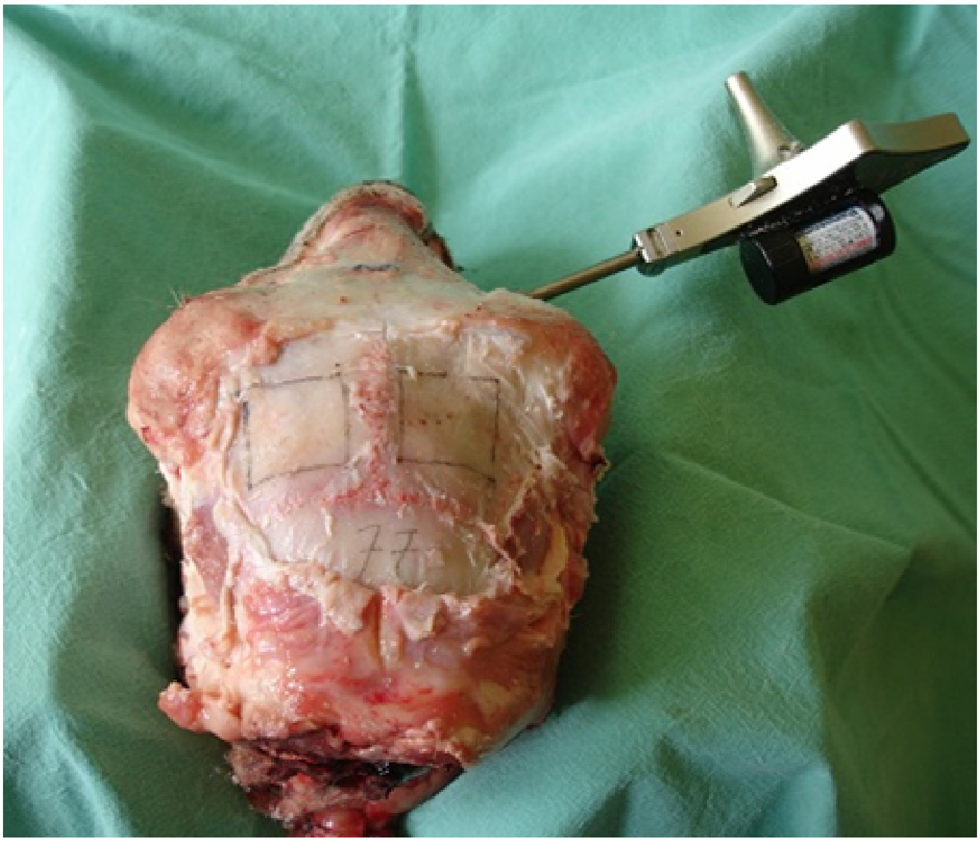


Figure 1: Right and left frontal areas and navigation marker

Point digitization was performed with the use of a pointer (by touching the pointer tip to the selected point) (Fig. 2). Position of the pointer relative to the tracker was recorded by the camera and evaluated by the software.

The digitization procedure was repeated three times running.

The first time, 25 points were digitized through a clear perforated template grid numbered from 1 to 25 at intervals of 5 mm. A monocortical graft was then taken from the frontal right bone. The outer table was reamed down to the diploe using a round burr. The frontal bone flap was then split with sharp bone splitters using the Tessier technique [16].

Figure 2: Acquisitions (Digitize) of the points after parietal harvest

The second time, another 25 points were digitized through a clear perforated template grid numbered from 26 to 51 at intervals of 5 mm (Fig.3).

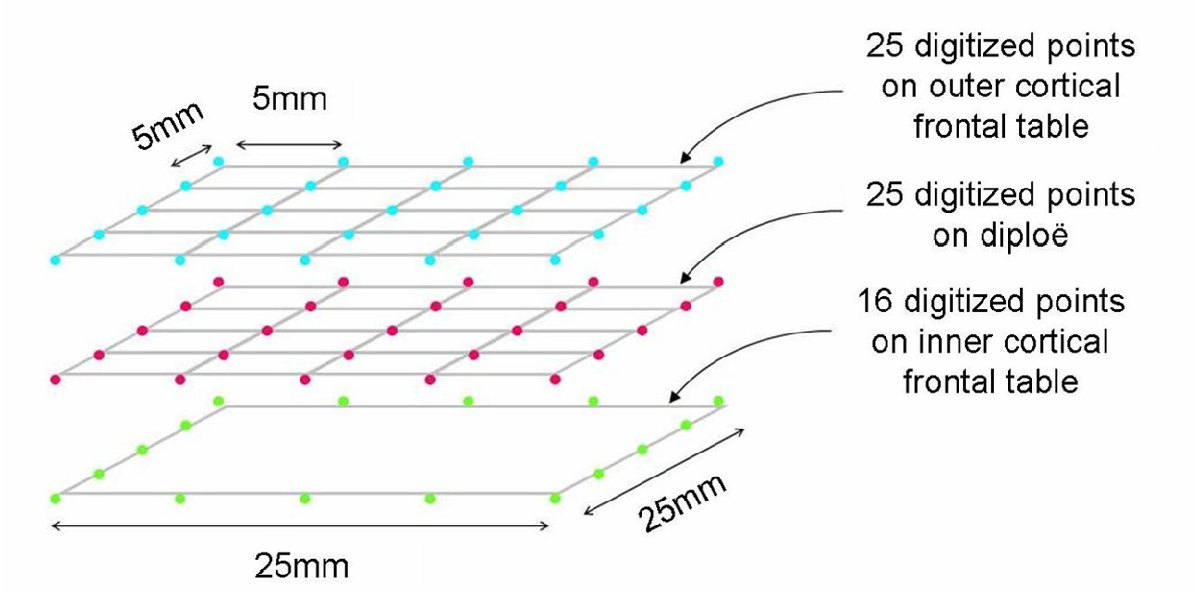


Figure 3: Palpated points for thickness calculations

The thickness of the harvested bone graft was measured based on the distances between these points.

After the impact, the inner table was cut out using a milling machine.

A third digitization was then performed through a clear perforated template grid numbered from 52 to 67 at intervals of 5 mm. The pointer tip was applied to the lowest point at the perimeter of the area.

Mean total thickness was calculated based on the 16 perimeter point's difference collected during the first and third digitization procedures. Mean thickness of the bone graft was calculated based on the 25 points difference collected during the first and second digitization procedures (Fig. 3).

Measurement of absorbed energy

The impact intensity was measured by the impact force absorbed by the skull.

We developed a pendulum Charpy impact testing machine in which the hammer was released from a height of one meter (Fig. 4) and stroke the target zone at a speed of 9.812 m/s^2 (i.e. under normal acceleration due to gravity). The energy absorbed by the impact was calculated by comparing the potential energy at the beginning and at the end of the test. The whole of the kinetic energy was absorbed by the skull. No bounce was noted when fracture occurred. At the beginning of the test, the swinging pendulum was in a horizontal position (checked with a spirit level). Therefore, the height of drop was one meter. In order to eliminate the energy generated by friction, self-aligning ball bearings were used to guide the axis of the pendulum.

Each specimen was firmly held in a vice in a slanted position so that the hammer surface was parallel to the bone surface.

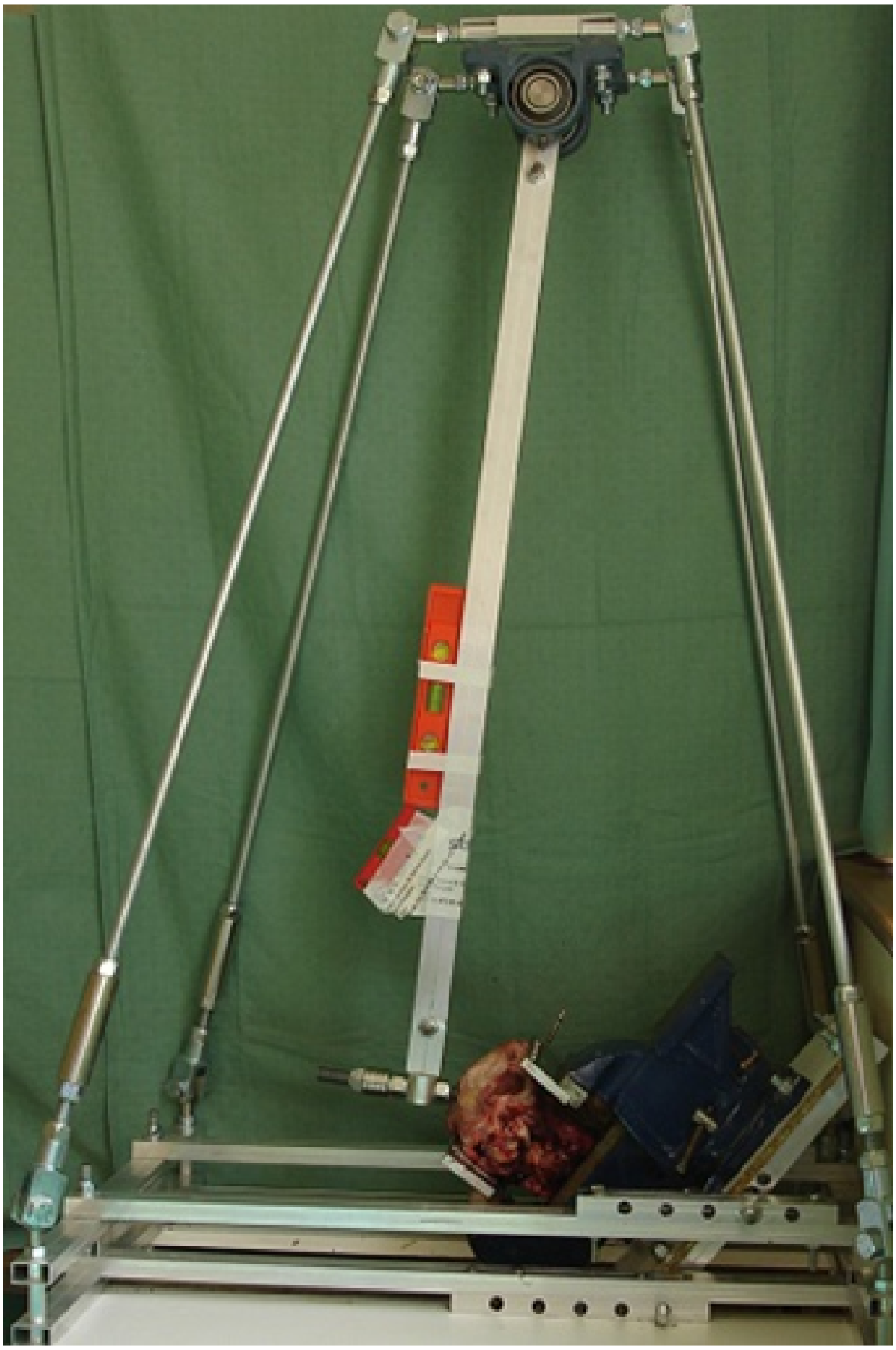


Figure 4: Test set-up

The rigid fixation provided by the vice and the secure connection of all component parts of the mounting eliminated the risk of energy loss.

$E_{absorbed\ during\ impact} = mgh$ (m = mass in kg, g = 9.812 m/s^2, h = 1 m)

The frontal target zone was a square of side length 25 mm. To fit this area we used a 14 mm diameter hammer. Loads were gradually increased to bone failure (Fig.5). A fracture was defined by a depressed skull fracture.

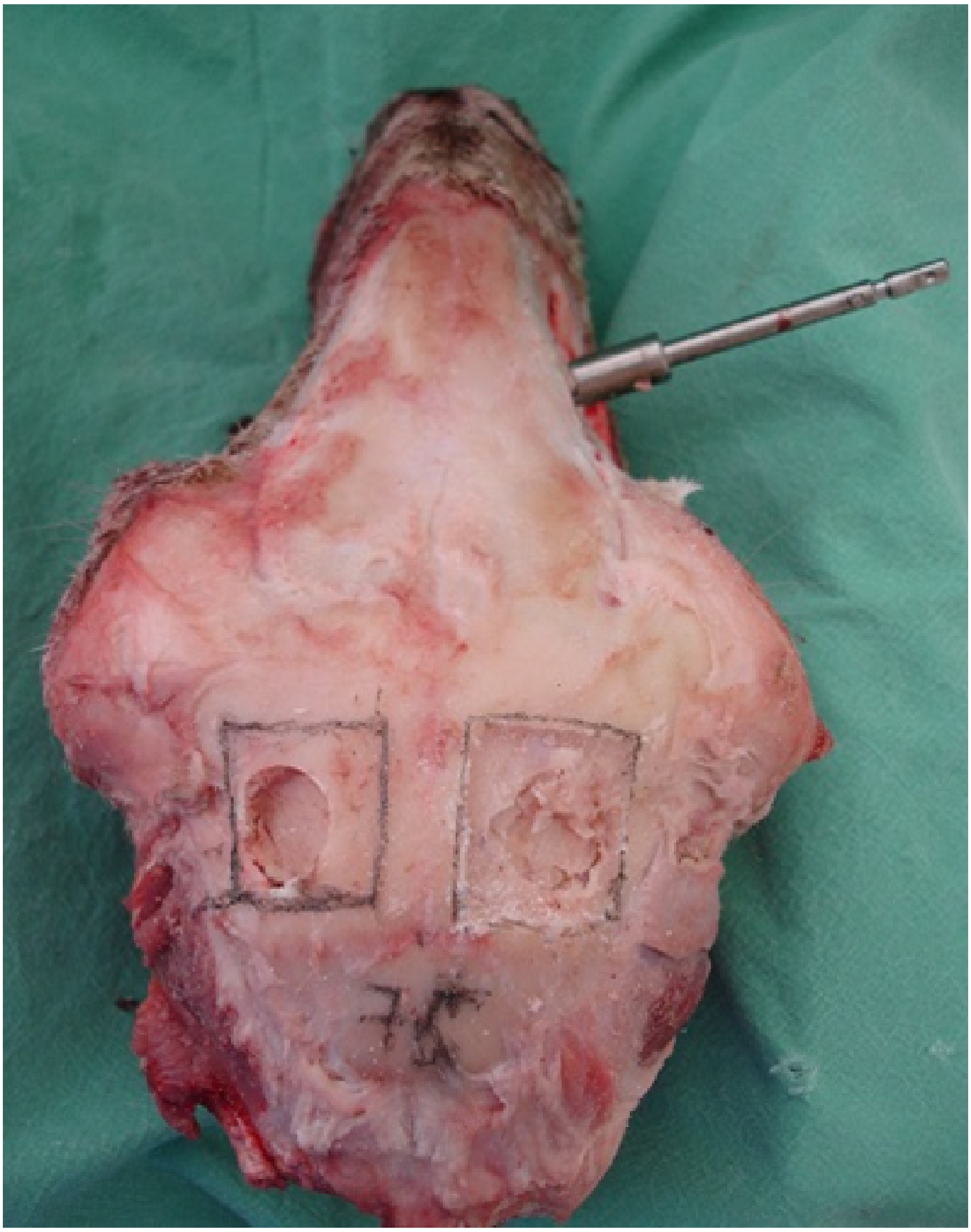


Figure 5: Impact on frontal zone

Statistical method

A paired *t*-test was used for statistical analysis of the difference in frontal bone thickness between the right and left sides.

A paired *t*-test was also used for statistical analysis of impact resistance on donor right side versus intact left side (left side was used as control).

A *t*-test was used for the statistical analysis of chocks' numbers on right and left sides.

A Pearson test was used to evaluate the correlation between thickness and strength of the frontal bone.

Results

Thickness measurement

Results are presented in Table 1.

	Left intact side	**Right harvest side**			**Left versus Right side**
	Total thickness	Total thickness	Thickness after harvest	Loss of thickness	Total thickness
Min	3.0mm	3.5mm	1.5mm	13%	-3.5mm
Max	8.0mm	10.0mm	8.0mm	57%	+2.0mm
Mean	5.7mm	6.3mm	4.4mm	31%*(1)	-0.6mm*(2)
IC95	0.8mm	1.1mm	1.0mm	7%	1mm

*(1) $p=2.10^{-18}$ (*t*-test), *(2) p=0,028 (*t*-test)

Table 1: Thickness of frontal areas on 34 sheep heads

Total thickness was measured on both sides (68 measures). Values ranged from 3.0 mm to 10 mm with a mean of 6 mm (SD = 1.4 mm).

Total thickness on the donor right side ranged from 3.5 mm to 10 mm with a mean of 6.3 mm (SD = 1.6 mm).

Total thickness on the intact left side ranged from 3 mm to 8 mm with a mean of 5.7 mm (SD = 1.1 mm).

The total frontal thickness on the right side was significantly higher (with a mean of 0.6 mm) than the total thickness on the left side (p = 0.028).

Bone graft thickness ranged from 0.5 mm to 3 mm with a mean of 1.9 mm (SD = 0.6 mm).

The ratio between the bone graft thickness and the total frontal bone thickness ranged from 15% to 55% with a mean of 31% (SD = 9%).

The loss of thickness due to the harvest was highly significant ($p = 2.10^{-19}$).

Energy

Results are presented in Table 2.

	Left intact side	Right harvest side	Loss of resistance (right/left after harvest)
Min	5.1J	3.5J	8%
Max	18.1J	6.0J	80%
Mean	9.1J	4.2J	49%*
IC95	2.5J	0.5J	12%

*$p=3.10^{-10}$ (unilateral paired Student test)

Table 2: Resistances of frontal areas on 34 sheep heads

The cracks were depressed on both sides of all 34 heads (100%).

The maximum absorbable energy at impact on the right side (removed before fracture) ranged from 3.5 J to 5.8 J with a mean of 4.2 J (SD = 0.7 J).

The maximum absorbable energy at impact on the left side (intact before fracture) ranged from 5.1 J to 18.1 J with a mean of 9.1 J (SD = 3.5 J).

Loss of strength

Results are presented in Table 2.

The difference of resistance between the intact left side and the harvested right side ranged from 8% to 80% with a mean of 49% (SD = 17%).

The loss of resistance due to the frontal bone harvest is highly significant ($p = 6.10^{-10}$).

Correlation between the frontal resistance and its thickness

The secondary aim of this study was to determine a correlation between the skull resistance and its thickness (Fig.6).

We calculated a significant Pearson correlation coefficient of 0.48 ($p = 0.004$), using the 34 results gathered on the harvested side and the 34 results on the intact side.

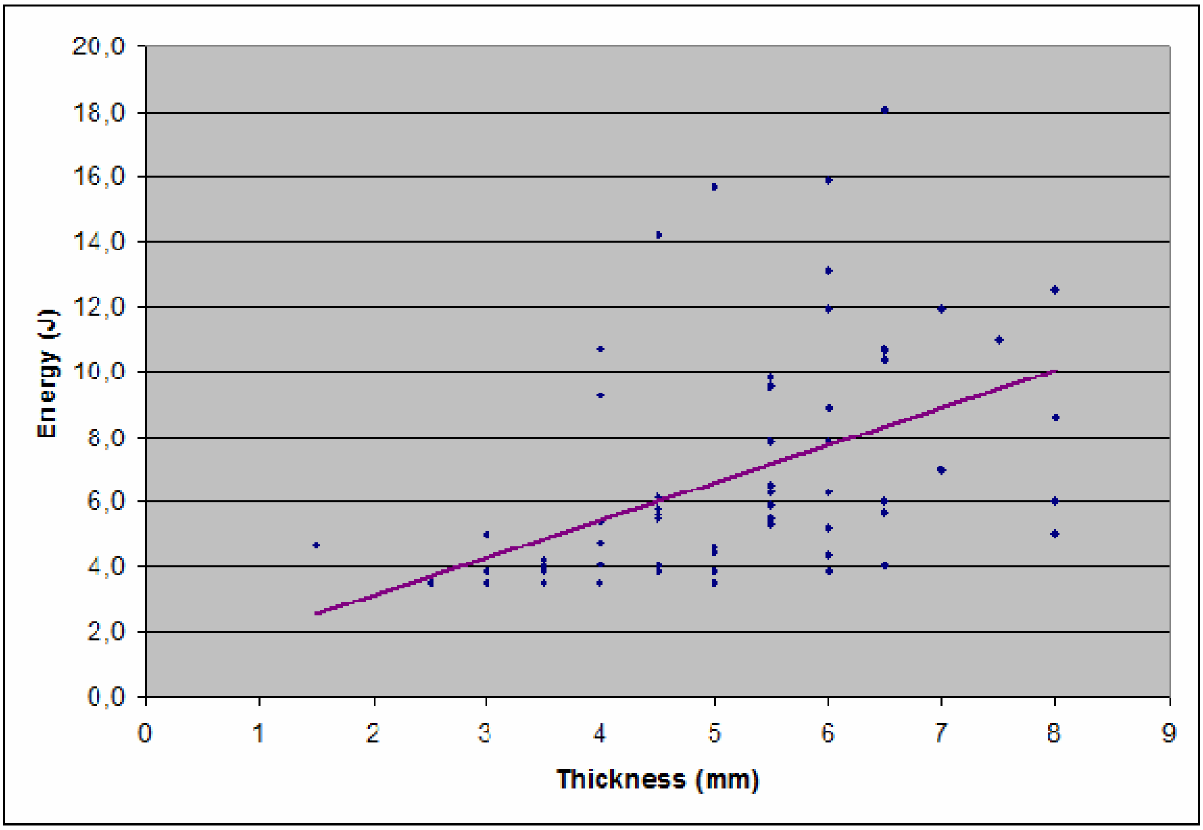


Figure 6: Correlation study between resistance and thickness of the frontal (Linear correlation coefficient: R = 0.48; p = 0.004)

Discussion

This study shows that a monocortical frontal bone harvest reduces the resistance of this area of 49%. It also demonstrates the existence of a correlation between the impact resistance and the frontal bone thickness.

Choice of the sheep

We performed this study on sheep skulls. This choice was made due to the animal size which allowed a decent study of the skull resistance with a system like - pendulum Charpy impact machine. The rabbit, the rat or the mouse are too small for this test. In pigs, parietal bones are too vertical and the frontal bones are totally pneumatised.

Choice of the frontal / parietal bone

In this study, we used the frontal bone. The parietal bone could not be removed due to its anatomic position which is very posterior. Contrary to what we read in literature [17] the parietal bone is unique in sheep [18] . As a consequence, it could not be used for our test.

The frontal bone is pair, flat and symmetrical bone. It is pneumatised in its anterior part and becomes bicortical with a diploe behind the corneal bone, becoming similar to the anatomic conditions of the parietal bone in humans.

Decrease of the frontal resistance and thickness/resistance correlation

This study performed on 34 sheep heads shows that a monocortical frontal bone harvest of 25 x 25 mm in sheep reduces the resistance of this area by 49%, in comparison with the intact contro lateral side. This loss of resistance is highly significant ($p = 6.10^{-10}$).

It also exists a positive correlation between the impact resistance and the frontal bone thickness ($p = 0.004$). This result also demonstrates that the resistance decreases significantly (with a mean of 49%) with the thickness (with a mean of 31%).

Moreover, the total thickness on the right side (harvested) was significantly higher than the thickness on the left side (intact). As a consequence, this difference increases the significant threshold of our results.

Total thickness of the target zone measured on both sides (68 measures) were ranged from 3.0 mm to 10 mm with a mean of 6 mm (SD = 1.4 mm).

On the human skull, Moreira reported a mean parietal bone thickness of 6.32 mm in 281 dry skulls [19]. In Sullivan's necropsy study [20] involving 37 patients, parietal bone thickness was 6.4 mm. The thickness of the posterior part of sheep frontal bone can be compare to the thickness of parietal human bone.

Prospects

We demonstrated through this study the loss of resistance of the skull on the harvested side. The reconstruction of the harvested area, using hydroxyapatite cement [21] is increasing. If this reconstruction allows the reduction of aesthetic relapses due to the depression, we do not know yet its effectiveness on resistance. This kind of study can’t be performed in humans for some obvious ethical reasons.

These results will allow us to carry out a study in sheep, to compare the resistance of the harvested frontal bone area and reconstructed with a new hydroxyapatite cement (Hydroset®). Results of this study will be developed later.

Acknowledgements

This study was financially supported by Stryker Company. Institut National de la Recherche Agronomique, Nouzilly (37380), France is gratefully acknowledged.

Conflict of interest statement

No financial support or benefits have been received by me or any co-authors, by any member of my (our) immediate family or any individual or entity with whom or with which I (we) have a relationship from any commercial source which is related directly or indirectly to the scientific work which is reported on in the article.

References

[1] Baccar MN, Laure B, Sury F, Romieux G, Bonin B, Goga D. [Pre-implantation apposition grafts for edentuous anterior maxillary. Retrospective study of 36 patients]. Rev Stomatol Chir Maxillofac 2005;106: 149-51.

[2] Gutta R, Waite PD. Cranial bone grafting and simultaneous implants: a submental technique to reconstruct the atrophic mandible. Br J Oral Maxillofac Surg 2008;46: 477-9.

[3] Iizuka T, Smolka W, Hallermann W, Mericske-Stern R. Extensive augmentation of the alveolar ridge using autogenous calvarial split bone grafts for dental rehabilitation. Clin Oral Implants Res 2004;15: 607-15.

[4] Crespi R, Vinci R, Cappare P, Gherlone E, Romanos GE. Calvarial versus iliac crest for autologous bone graft material for a sinus lift procedure: a histomorphometric study. Int J Oral Maxillofac Implants 2007;22: 527-32.

[5] Le Lorc'h-Bukiet I, Tulasne JF, Llorens A, Lesclous P. Parietal bone as graft material for maxillary sinus floor elevation: structure and remodeling of the donor and of recipient sites. Clin Oral Implants Res 2005;16: 244-9.

[6] Emsen IM, Benlier E. Autogenous calvarial bone graft versus reconstruction with alloplastic material in treatment of saddle nose deformities: a two-center comparative study. J Craniofac Surg 2008;19: 466-75.

[7] Himy S, Zink S, Bodin F, Bruant-Rodier C, Wilk A, Meyer C. [Calvarial bone grafting in augmentation rhinoplasty. Long-term results]. Rev Stomatol Chir Maxillofac 2009;110: 256-62.

[8] Siddique SA, Mathog RH. A comparison of parietal and iliac crest bone grafts for orbital reconstruction. J Oral Maxillofac Surg 2002;60: 44-50; discussion 50-2.

[9] Wolfe SA, Ghurani R, Podda S, Ward J. An examination of posttraumatic, postsurgical orbital deformities: conclusions drawn for improvement of primary treatment. Plast Reconstr Surg 2008;122: 1870-81.

[10] Cannella DM, Hopkins LN. Superior sagittal sinus laceration complicating an autogenous calvarial bone graft harvest: report of a case. J Oral Maxillofac Surg 1990;48: 741-3.

[11] Kline RM, Jr., Wolfe SA. Complications associated with the harvesting of cranial bone grafts. Plast Reconstr Surg 1995;95: 5-13; discussion 14-20.

[12] Wilkinson HA. Autogeneic skull bone graft (Letter). Neurosurgery 1987;21: 760.

[13] Young VL, Schuster RH, Harris LW. Intracerebral hematoma complicating split calvarial bone-graft harvesting. Plast Reconstr Surg 1990;86: 763-5.

[14] Marchac D, Greensmith A. Long-term experience with methylmethacrylate cranioplasty in craniofacial surgery. J Plast Reconstr Aesthet Surg 2008;61: 744-52; discussion 753.

[15] Costantino PD, Chaplin JM, Wolpoe ME, Catalano PJ, Sen C, Bederson JB, Govindaraj S. Applications of fast-setting hydroxyapatite cement: cranioplasty. Otolaryngol Head Neck Surg 2000;123: 409-12.

[16] Tessier P, Kawamoto H, Posnick J, Raulo Y, Tulasne JF, Wolfe SA. Taking calvarial grafts--tools and techniques: VI. The splitting of a parietal bone "flap". Plast Reconstr Surg 2005;116: 74S-88S; discussion 92S-94S.

[17] Kuemmerle JM, Oberle A, Oechslin C, Bohner M, Frei C, Boecken I, von Rechenberg B. Assessment of the suitability of a new brushite calcium phosphate cement for cranioplasty - an experimental study in sheep. J Craniomaxillofac Surg 2005;33: 37-44.

[18] Cuvier G. Leçon d'Anatomie Comparée, Tome 2, Crochard, Paris,1835, p 26.

[19] Moreira-Gonzalez A, Papay FE, Zins JE. Calvarial thickness and its relation to cranial bone harvest. Plast Reconstr Surg 2006;117: 1964-71.

[20] Sullivan WG, Smith AA. The split calvarial graft donor site in the elderly: a study in cadavers. Plast Reconstr Surg 1989;84: 29-31.

[21] Rupprecht S, Merten HA, Kessler P, Wiltfang J. Hydroxyapatite cement (BoneSource) for repair of critical sized calvarian defects--an experimental study. J Craniomaxillofac Surg 2003;31: 149-53.

Perspectives - Conclusion

La perte de résistance du crâne humain après prélèvement calvarial monocortical est significative ($p=10^{-10}$). Elle est en moyenne diminuée de 36% du côté prélevé par rapport au côté non prélevé. Cependant, les complications graves au niveau de site de prélèvement sont rares. Cette étude montre que les risques de fracture en cas de choc direct sur la zone de prélèvement ne sont pas négligeables. Il est donc important d'en informer le patient.

Cependant, notre étude a été réalisée sans le scalp. Des essais préliminaires avaient été menés avec le scalp en place. Ils avaient montré qu'à chaque choc, celui-ci subissait un écrasement irréversible par le percuteur, avec délabrement comminutif après 3 chocs. Le rôle du scalp n'était donc plus assuré à partir du quatrième choc. Il est évident qu'en clinique humaine le scalp joue un rôle amortisseur important.

D'autre part, notre étude a évalué la résistance du crane de la zone prélevée. Elle ne reflète donc pas la résistance au choc de l'ensemble de la voute crânienne. Dans ce cas nous pouvons extrapoler les résultats de cette étude en clinique humaine, uniquement si le choc reçu par le patient est situé sur la zone prélevée. Le choc doit venir du haut (choc contre une poutre, coup de bâte de base-ball, chute de pierre…), ce qui est assez rare. Les accidents de la voie publique ne donnent pas ce type de chocs. De plus, nous ne savons pas quelle sera la résistance du crane si le choc est subit à distance de la zone prélevée.

Notre étude est l'une des rares réalisée sur têtes de cadavres fraîches pleines. Le protocole décrit pourra être reproduit virtuellement. Nos résultats pourront servir pour la validation de modèles d'éléments finis dynamiques (DFEA).

Dans notre étude la prise de greffon pariétal correspond à une diminution d'épaisseur de 40% et entraîne une diminution de résistance de 36%. L'étude de la corrélation entre la résistance aux chocs et l'épaisseur de l'os pariétal confirme cela.

Bien que modérée (R=0,46), cette corrélation est significative (p=0,0001 au test de Pearson). La corrélation est de signe positif, ce qui valide le fait que plus l'épaisseur de l'os pariétal est importante, plus la résistance est importante mais cette résistance n'est pas uniquement due à l'épaisseur. Le rayon de courbure de la table externe était significativement supérieur au rayon de courbure de la table interne ($p=10^{-13}$). Ce résultat, ainsi que la légère différence entre la diminution d'épaisseur et la perte de résistance (4%) laisserait à penser que la table interne serait plus résistante que la table externe.

Dans cette thèse nous avons montré que la perte de résistance occasionnée par un prélèvement crânien était en moyenne de 36% chez l'homme et de 49% chez le mouton. La reconstruction crânienne par biomatériau (*Marchac 2008*) et notamment par ciments à base d'hydroxyapatite est en expansion (*Costantino 2000, Kuemmerle 2005*, *Matic 2004*, *Rupprecht 2003*, *Wiltfang 2004, Zhou 2007, Zins 2008*). Le comblement du site de prélèvement pariétal par biomatériau n'est pas systématique. Si cette reconstruction permet de diminuer la dépression postopératoire, pourrait-elle permettre de retrouver une résistance du crâne similaire à celle du crâne initial ?

Nous sommes dans l'impossibilité d'effectuer un travail de recherche sur la résistance du crâne humain pour des raisons éthiques évidentes.

Nous avons donc choisi de mener cette étude sur un modèle animal (la brebis de race Ile de France) au niveau de l'os frontal. En effet l'os pariétal de la Brebis ne permet pas un protocole reproductible en raison de sa taille et de son inclinaison (*Cuvier 1835*).

Le but de l'étude sera d'évaluer la résistance du crâne de brebis après cranioplastie par Hydroset® (ciment hydroxyapatite – Stryker) par rapport au crâne intact controlatéral.

.

Les animaux seront opérés et surveillés à l'Institut National de Recherche Agronomique de Nouzilly (37) selon les normes réglementaires applicables aux animaux de laboratoire.

Trente brebis seront opérées sous anesthésie générale.

Un prélèvement d'un volet uni cortical frontal postérieur de 25mm de large sur 25mm sera réalisé. Ce prélèvement monocortical sera comblé pat un ciment hydroxyapatite (Hydroset –Sryker). Les mesures des épaisseurs seront réalisées selon la méthode précedemment utilisée, avec le système de navigation optoélectronique.

La brebis sera placée dans un box pour le réveil et les 24 premières heures post-opératoires. Aucun suivi ne sera nécessaire après la surveillance de 24 heures post-opératoires. Les brebis seront mises au champ et en étable pendant un an.

La seconde partie de l'étude aura lieu à 12 mois. Les brebis seront sacrifiées.

La tête de l'animal sera placée dans un étau. L'abord sera repris et la dissection symétrisée. A l'aide du système de navigation, divers points préétablis et la cranioplastie seront repérés. Les tests sur la résistance du crane seront effectués successivement sur la zone reconstruite droite puis du côté sain controlatéral grâce au mouton-pendule de Charpy.

Le reste de la cranioplastie sera prélevé et analysé histologiquement avec un compte cellulaire des macrophages, ostéoclastes, ostéoblastes pour évaluer la recolonisation osseuse du biomatériau.

Bibliographie

1 Allsop DL, Perl TR, Warner CY. Force/Deflexion and fracture Characteristics of the temporo-parietal region of the human head. *35th Stapp Car Crash Conference, San Diego, California, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1991:269-78.

2 Allsop DL, Warner CY, Wille MG, Schneider DC, Nahum AM. Facial impact response- a comparison of the hybrid III dummy and human cadaver. *32nd Stapp Car Crash Conference, Atlanta, Georgia, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1988:139-55.

3 Autuori B, Bruyere-Garnier K, Morestin F, Brunet M, Verriest JP. Finite element modeling of the head skeleton with a new local quantitative assessment approach. *IEEE transactions on bio-medical engineering* 2006;53:1225-32.

4 Baccar MN, Laure B, Sury F, Romieux G, Bonin B, Goga D. [Pre-implantation apposition grafts for edentuous anterior maxillary. Retrospective study of 36 patients]. *Revue de stomatologie et de chirurgie maxillo-faciale* 2005;106:149-51.

5 Bruyere K, Bermond F, Bouquet R, Caire Y, Ramet M, Voiglio E. Human maxilla bone response to 30° oriented impacts and comparison with frontal bone impacts. *44th Association for the Advancement of Automotive Medicine Conference, October 2-4, Chicago* 2000:219-34.

6 Camacho DL, Hopper RH, Lin GM, Myers BS. An improved method for finite element mesh generation of geometrically complex structures with application to the skullbase. *J Biomech* 1997;30:1067-70.

7 Cannella DM, Hopkins LN. Superior sagittal sinus laceration complicating an autogenous calvarial bone graft harvest: report of a case. *J Oral Maxillofac Surg* 1990;48:741-3.

8 Charpy G. Note sur l'essai des métaux à la flexion par choc de barreaux entaillés. *Mémoire et compte-rendus de
la Société des ingénieurs civils de France* 1901.

9 Cohen M, Figueroa AA, Haviv Y, Schafer ME, Aduss H. Iliac versus cranial bone for secondary grafting of residual alveolar clefts. *Plastic and reconstructive surgery* 1991;87:423-7; discussion 8.

10 Costantino PD, Chaplin JM, Wolpoe ME, et al. Applications of fast-setting hydroxyapatite cement: cranioplasty. *Otolaryngol Head Neck Surg* 2000;123:409-12.

11 Crespi R, Vinci R, Cappare P, Gherlone E, Romanos GE. Calvarial versus iliac crest for autologous bone graft material for a sinus lift procedure: a histomorphometric study. *The International journal of oral & maxillofacial implants* 2007;22:527-32.

12 Cuvier G. Leçon d'Anatomie Comparée. 1835;2:26.

13 Dupoirieux L, Siciliano S, Savastano G, Souyris F. [The advantage of the autologous parietal bone graft in posttraumatic rhinoplasty]. *Minerva stomatologica* 1994;43:507-12.

14 Eichhorn W, Blessmann M, Pohlenz P, et al. Primary osteoplasty using calvarian bone in patients with cleft lip, alveolus and palate. *J Craniomaxillofac Surg* 2009;37:429-33.

15 Elahi MM, Watkin KL, Hakim MS, Schloss MD, Lessard ML. A new predictive modality of cranial bone thickness. *Annals of plastic surgery* 1999;42:651-7.

16 Fearon JA. A magnetic resonance imaging investigation of potential subclinical complications after in situ cranial bone graft harvest. *Plastic and reconstructive surgery* 2000;105:1935-9.

17 Fleuridas G, Favre E, Paranque A, et al. [Parietal grafts in maxillofacial and pre-implant surgery]. *Revue de stomatologie et de chirurgie maxillo-faciale* 1998;99:165-9.

18 Grenadier MR. Using the calvarial bone graft for implant reconstruction. *Dental implantology update* 1992;3:33-6.

19 Gupta HS, Zioupos P. Fracture of bone tissue: The 'hows' and the 'whys'. *Med Eng Phys* 2008;30:1209-26.

20 Gutta R, Waite PD. Cranial bone grafting and simultaneous implants: a submental technique to reconstruct the atrophic mandible. *The British journal of oral & maxillofacial surgery* 2008;46:477-9.

21 Gutta R, Waite PD. Outcomes of calvarial bone grafting for alveolar ridge reconstruction. *The International journal of oral & maxillofacial implants* 2009;24:131-6.

22 Hampson D. Facial injury: a review of biomechanical studies and test procedures for facial injury assessment. *J Biomech* 1995;28:1-7.

23 Harsha BC, Turvey TA, Powers SK. Use of autogenous cranial bone grafts in maxillofacial surgery: a preliminary report. *J Oral Maxillofac Surg* 1986;44:11-5.

24 Hatipoglu HG, Ozcan HN, Hatipoglu US, Yuksel E. Age, sex and body mass index in relation to calvarial diploe thickness and craniometric data on MRI. *Forensic Sci Int* 2008;182:46-51.

25 Himy S, Zink S, Bodin F, Bruant-Rodier C, Wilk A, Meyer C. [Calvarial bone grafting in augmentation rhinoplasty. Long-term results]. *Revue de stomatologie et de chirurgie maxillo-faciale* 2009;110:256-62.

26 Hodgson VR. Tolerance of the facial bones to impact. *Am. J. Anat.* 1967;120:113-22.

27 Hodgson VR, Brinn J, Thomas LM, Greengerg SW. Fracture behaviour of the skull frontal bone against cylindrical surfaces. *14th Stapp Car Crash Conference, Ann Arbor, Michigan, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1970:341-55.

28 Iizuka T, Smolka W, Hallermann W, Mericske-Stern R. Extensive augmentation of the alveolar ridge using autogenous calvarial split bone grafts for dental rehabilitation. *Clinical oral implants research* 2004;15:607-15.

29 Jackson IT, Helden G, Marx R. Skull bone grafts in maxillofacial and craniofacial surgery. *J Oral Maxillofac Surg* 1986;44:949-55.

30 Jackson IT, Pellett C, Smith JM. The skull as a bone graft donor site. *Annals of plastic surgery* 1983;11:527-32.

31 Jung YS, Kim HJ, Choi SW, Kang JW, Cha IH. Regional thickness of parietal bone in Korean adults. *Int J Oral Maxillofac Surg* 2003;32:638-41.

32 Keen M. Complications of harvesting cranial bone grafts(Letter). *Plastic and reconstructive surgery* 1995;96:1753.

33 Kleiven S, von Holst H. Consequences of head size following trauma to the human head. *J Biomech* 2002;35:153-60.

34 Kline RM, Jr., Wolfe SA. Complications associated with the harvesting of cranial bone grafts. *Plastic and reconstructive surgery* 1995;95:5-13; discussion 4-20.

35 Koenig WJ, Donovan JM, Pensler JM. Cranial bone grafting in children. *Plastic and reconstructive surgery* 1995;95:1-4.

36 Krastinova-Lolov D. Mask lift and facial aesthetic sculpturing. *Plastic and reconstructive surgery* 1995;95:21-36.

37 Kuemmerle JM, Oberle A, Oechslin C, et al. Assessment of the suitability of a new brushite calcium phosphate cement for cranioplasty - an experimental study in sheep. *J Craniomaxillofac Surg* 2005;33:37-44.

38 Kusiak JF, Zins JE, Whitaker LA. The early revascularization of membranous bone. *Plastic and reconstructive surgery* 1985;76:510-6.

39 Le Lorc'h-Bukiet I, Tulasne JF, Llorens A, Lesclous P. Parietal bone as graft material for maxillary sinus floor elevation: structure and remodeling of the donor and of recipient sites. *Clinical oral implants research* 2005;16:244-9.

40 Lynnerup N. Cranial thickness in relation to age, sex and general body build in a Danish forensic sample. *Forensic Sci Int* 2001;117:45-51.

41 Lynnerup N, Astrup JG, Sejrsen B. Thickness of the human cranial diploe in relation to age, sex and general body build. *Head Face Med* 2005;1:13.

42 Maniglia AJ, Swim S. Parietal bone graft and titanium plate fixation in nasal reconstruction. *The Laryngoscope* 1993;103:1066-72.

43 Marchac D, Greensmith A. Long-term experience with methylmethacrylate cranioplasty in craniofacial surgery. *J Plast Reconstr Aesthet Surg* 2008;61:744-52; discussion 53.

44 Matic DB, Manson PN. Biomechanical analysis of hydroxyapatite cement cranioplasty. *The Journal of craniofacial surgery* 2004;15:415-22; discussion 22-3.

45 Melega JM, Zani R, Gomes PR. [Repair of the orbital floor with a parietal bone graft]. *Revista paulista de medicina* 1984;102:223-5.

46 Melvin JW, Evans FG. A strain energy approach to the mechanics of skull fracture. *15th Stapp Car Crash Conference, San Diego, California, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1971:666-85.

47 Melvin JW, Shee TR. Facial injury assessment techniques. *12th International Technical Conference on Experimental Safety Vehicle, May 29 - June 1, Göteborg, Sweden. National Highway Traffic Safety Administration* 1989:608-17.

48 Melvin JW, Shee TR. Facial injury assessment techniques. *12th International Technical Conference on Experimental Safety Vehicle, May 29 - June 1, Göteborg, Sweden. National Highway Traffic Safety Administration* 1989:608-17.

49 Moreira-Gonzalez A, Papay FE, Zins JE. Calvarial thickness and its relation to cranial bone harvest. *Plastic and reconstructive surgery* 2006;117:1964-71.

50 Motherway J, Doorly MC, Curtis M, Gilchrist MD. Head impact biomechanics simulations: A forensic tool for reconstructing head injury? *Legal Medicine* 2009;11:S220-S2.

51 Nahum AM, Gatts, J. D., Gadd, C. W., Danforth, J. Impact tolerance of the skull and face. *12th Stapp Car Crash Conference, Detroit, Michigan, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1968:302-16.

52 Nyquist GW, Cavanaugh JM, Goldberg SJ, King AI. Facial impact tolerance and response. *30th Stapp Car Crash Conference, San Diego, Californie, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers,* 1986:379-400.

53 Ono K. Human head tolerance to sagittal impact reliable estimation deduced from experimental head injury using subhuman primates and human cadaver skulls. *24th Stapp Car Crash Conference, Troy, Michigan, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1980:103-60.

54 Peterson J, Dechow PC. Material properties of the inner and outer cortical tables of the human parietal bone. *Anat Rec* 2002;268:7-15.

55 Peterson J, Dechow PC. Material properties of the human cranial vault and zygoma. *Anat Rec A Discov Mol Cell Evol Biol* 2003;274:785-97.

56 Raulo Y, Baruch J. [Use of the calvarium for bone grafting in cranio-maxillo-facial surgery]. *Chirurgie* 1990;116:359-62.

57 Rupprecht S, Merten HA, Kessler P, Wiltfang J. Hydroxyapatite cement (BoneSource) for repair of critical sized calvarian defects--an experimental study. *J Craniomaxillofac Surg* 2003;31:149-53.

58 Schneider DC, Nahum, A. M. Impact studies of facial bones and skull. *16th Stapp Car Crash Conference, Detroit, Michigan, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers.* 1972:186-203.

59 Shipchandler TZ, Chung BJ, Alam DS. Saddle nose deformity reconstruction with a split calvarial bone L-shaped strut. *Arch Facial Plast Surg* 2008;10:305-11.

60 Siciliano S, Savastano G, Reychler H. [The role of autologous parietal bone graft in alveolar cleft]. *Minerva stomatologica* 1995;44:389-95.

61 Siddique SA, Mathog RH. A comparison of parietal and iliac crest bone grafts for orbital reconstruction. *J Oral Maxillofac Surg* 2002;60:44-50; discussion -2.

62 Smith JD, Abramson M. Membranous vs endochondrial bone autografts. *Arch Otolaryngol* 1974;99:203-5.

63 Sullivan WG, Smith AA. The split calvarial graft donor site in the elderly: a study in cadavers. *Plastic and reconstructive surgery* 1989;84:29-31.

64 Tellioglu AT, Yilmaz S, Baydar S, Tekdemir I, Elhan AH. Computed tomographic evaluation before cranial bone harvesting to avoid unexpected hazards during aesthetic procedures. *Aesthetic Plast Surg* 2001;25:198-201.

65 Tessier P, Kawamoto H, Posnick J, Raulo Y, Tulasne JF, Wolfe SA. Taking calvarial grafts--tools and techniques: VI. The splitting of a parietal bone "flap". *Plastic and reconstructive surgery* 2005;116:74S-88S; discussion 92S-4S.

66 Tessier P, Kawamoto H, Posnick J, Raulo Y, Tulasne JF, Wolfe SA. Complications of harvesting autogenous bone grafts: a group experience of 20,000 cases. *Plastic and reconstructive surgery* 2005;116:72S-3S; discussion 92S-4S.

67 Tessier P, Kawamoto H, Posnick J, Raulo Y, Tulasne JF, Wolfe SA. Taking calvarial grafts, either split in situ or splitting of the parietal bone flap ex vivo--tools and techniques: V. A 9650-case experience in craniofacial and maxillofacial surgery. *Plastic and reconstructive surgery* 2005;116:54S-71S; discussion 92S-4S.

68 Tulasne JF. [Harvesting the parietal bone]. *Revue de stomatologie et de chirurgie maxillo-faciale* 2003;104:159-61.

69 Verschueren P, Delye H, Depreitere B, et al. A new test set-up for skull fracture characterisation. *J Biomech* 2007;40:3389-96.

70 Wilkinson HA. Autogeneic skull bone graft (Letter). *Neurosurgery* 1987;21:760.

71 Willinger R, Kang HS, Diaw B. Three-dimensional human head finite-element model validation against two experimental impacts. *Ann Biomed Eng* 1999;27:403-10.

72 Wiltfang J, Kessler P, Buchfelder M, Merten HA, Neukam FW, Rupprecht S. Reconstruction of skull bone defects using the hydroxyapatite cement with calvarial split transplants. *J Oral Maxillofac Surg* 2004;62:29-35.

73 Wolfe SA, Berkowitz S. The use of cranial bone grafts in the closure of alveolar and anterior palatal clefts. *Plastic and reconstructive surgery* 1983;72:659-71.

74 Wolfe SA, Ghurani R, Podda S, Ward J. An examination of posttraumatic, postsurgical orbital deformities: conclusions drawn for improvement of primary treatment. *Plastic and reconstructive surgery* 2008;122:1870-81.

75 Yoganandan N. Steering Wheel induced facial trauma. *32nd Stapp Car Crash Conference, Atlanta, Georgia, USA. Warrendale, Pennsylvania, USA: Society of Automotive Engineers* 1988:45-69.

76 Yoganandan N, Pintar FA. Biomechanics of temporo-parietal skull fracture. *Clin Biomech (Bristol, Avon)* 2004;19:225-39.

77 Yoganandan N, Pintar FA, Sances A, Jr., et al. Biomechanics of skull fracture. *J Neurotrauma* 1995;12:659-68.

78 Young VL, Schuster RH, Harris LW. Intracerebral hematoma complicating split calvarial bone-graft harvesting. *Plastic and reconstructive surgery* 1990;86:763-5.

79 Zanaret M, Bouvier C, Bonnefille E, Estublier N, Giovanni A. [The use of calvarial bone in nasal reconstruction]. *Ann Otolaryngol Chir Cervicofac* 1999;116:16-26.

80 Zhou AJ, Peel SA, Clokie CM. An evaluation of hydroxyapatite and biphasic calcium phosphate in combination with Pluronic F127 and BMP on bone repair. *The Journal of craniofacial surgery* 2007;18:1264-75.

81 Zins JE, Moreira-Gonzalez A, Parikh A, Arslan E, Bauer T, Siemionow M. Biomechanical and histologic evaluation of the Norian craniofacial repair system and Norian Craniofacial Repair System Fast Set Putty in the long-term reconstruction of full-thickness skull defects in a sheep model. *Plastic and reconstructive surgery* 2008;121:271e-82e.

82 Zins JE, Whitaker LA. Membranous versus endochondral bone: implications for craniofacial reconstruction. *Plastic and reconstructive surgery* 1983;72:778-85.

Boris LAURE

RESISTANCE DU CRANE APRES PRELEVEMENT CALVARIAL MONOCORTICAL

Résumé

Le prélèvement crânien monocortical pourrait affaiblir la zone prélevée et exposer à des complications.
Nous avons conçu un mouton pendule de Charpy validé sur 12 têtes de cadavres humains. L'énergie du choc était augmentée jusqu'à fracture de la zone pariétale. Pour mesurer l'épaisseur avec un système de navigation optoélectronique, nous avons comparé cinq méthodes non destructives.
Dans la deuxième partie, la quantification de la perte de résistance était réalisée sur 30 têtes humaines en comparant le choc maximal supportable avant fracture du côté prélevé avec le côté non prélevé.
La troisième partie de l'étude a été menée sur 34 têtes de cadavres de brebis.
La perte de résistance de la zone prélevée était de 36% ($p=1.10^{-10}$) avec une diminution d'épaisseur de 40%. La corrélation entre les deux paramètres était modérée ($R=0.46$) mais significative ($p<0,0001$). Chez la brebis, la diminution de résistance du côté prélevé était de 49% ($p=6.10^{-10}$).
Ces données nous permettrons de réaliser une étude animale, pour évaluer la résistance de la zone prélevée reconstruite par un ciment d'hydroxyapatite.

Mots clés : os pariétal, site donneur, épaisseur, calvaria, crane.

Résumé en anglais

The monocortical parietal bone graft could decrease the strength of the donor site. Complication could occur.
We performed a Charpy impact machine and validated it on 12 human cadaver heads. The chock energy was increased until the fracture of the target zone. The thickness measurement was performed with an optoelectronic navigation device. We compared 5 non destructive methods. In the second part, the quantification of the resistance loss was performed on 30 human cadaver heads. The maximum impact resistance of bone on the donor side was compared with the intact side. The third part of the study was performed on 34 sheep cadaver heads.
Loss of strength at the donor site was 36% ($p=1.10^{-10}$) for 40% loss of thickness. Although correlation between these two parameters was rather moderate ($R=0.46$), it was highly significant ($p<0.0001$). On sheep, the loss of strength at the donor site was 49% ($p=6.10^{-10}$).
Bone removal results in a highly loss of strength on human and sheep. These data will permit to perform an animal study to evaluate the resistance of the harvest cranial zone rebuilt with hydroxyapatite cement.

Key words: parietal bone, donor site, thickness, calvaria, skull