Computerized Medical Imaging and Graphics 38 (2014) 675–682

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

journal homepage: www.elsevier.com/locate/compmedimag

Parametric mapping and quantitative analysis of the human calvarium

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ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form 27 June 2014
Accepted 30 June 2014

Keywords:
Human calvaria
Computed tomography
Density
Thickness
Parametric maps

ABSTRACT

In this paper we report how thickness and density vary over the calvarium region of a collection of human skulls. Most previous reports involved a limited number of skulls, with a limited number of measurement sites per skull, so data in the literature are sparse. We collected computer tomography (CT) scans of 51 ex vivo human calvaria, and analyzed these in silico using over 2000 measurement sites per skull. Thickness and density were calculated at these sites, for the three skull layers separately and combined, and were mapped parametrically onto the skull surfaces to examine the spatial variations per skull. These were found to be highly variable, and unique descriptors of the individual skulls. Of the three skull layers, the thickness of the inner cortical layer was found to be the most variable, while the least variable was the outer cortical density.

1. Introduction

The human cranium has been studied from many perspectives, ranging from forensics [1–3] fracture mechanics [4], developmental anatomy [5,6] to acoustics [7–10] and radiology [11]. Now, the emerging field of transcranial focused ultrasound (TcFUS) [12] brings a new set of reasons to examine the material properties of the human skull. TcFUS employs large hemispherical multi-element arrays [13,14], designed to transmit acoustic energy over a distributed cranial surface. With appropriate phase aberration correction techniques such as described in [11], this produces a highly contained intracranial focus while minimizing the effects of skull heating. For this reason it is important to characterize how the skull anatomy varies over a wider area than is necessary for small-footprint diagnostic ultrasound transducers. While these diagnostic transducers typically transmit through the temporal bone 'window', the TcFUS transducer transmits over much of the calvarium, comprised of the parietal, frontal and occipital bones. Modern high-resolution CT scanners can provide much insight into the properties of the calvarium, such as thickness and density, over the entirety of this region and in a continuous fashion. CT images may then be reconstructed and measured in a virtual 3D coordinate space. The number of points used, and their location on the calvarium may be dictated by a particular application. In the case of TcFUS this may associated with the number of transmitting elements in the hemispheric array, their spatial coordinates and the location of the intracranial focus. While the region of the skull studied in this manner is pertinent to that application, this is not the entirety of the anatomy available for measurement. To expand the region of measurement we generalized the hemispherical arrangement of points surrounding the calvarium so that the radius and point-count could be user-defined. This study reports on our work to establish a database of CT images for a large number of human calvaria, along with anatomical measurements of thickness and density. These parameters can be mapped parametrically onto the skull surface to gain insight as to how they vary, both intra- and inter-individually. To our knowledge, this paper is the first to include a large number of calvaria along with a high number of measurement points per skull. While our own motivation for this project was to better understand the effects of skull anatomy on the acoustic field produced by a TcFUS device, a milestone for this is the characterization of the skull anatomical variability, which is the subject of this paper.

2. Materials and methods

2.1. Skull specimens

Human cadaver skull specimens were used in this study. We used 51 calvaria, obtained from the UCSD Medical School Division of Anatomy, along with vital statistic data pertaining to donor gender,

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http://dx.doi.org/10.1016/j.compmedimag.2014.06.022

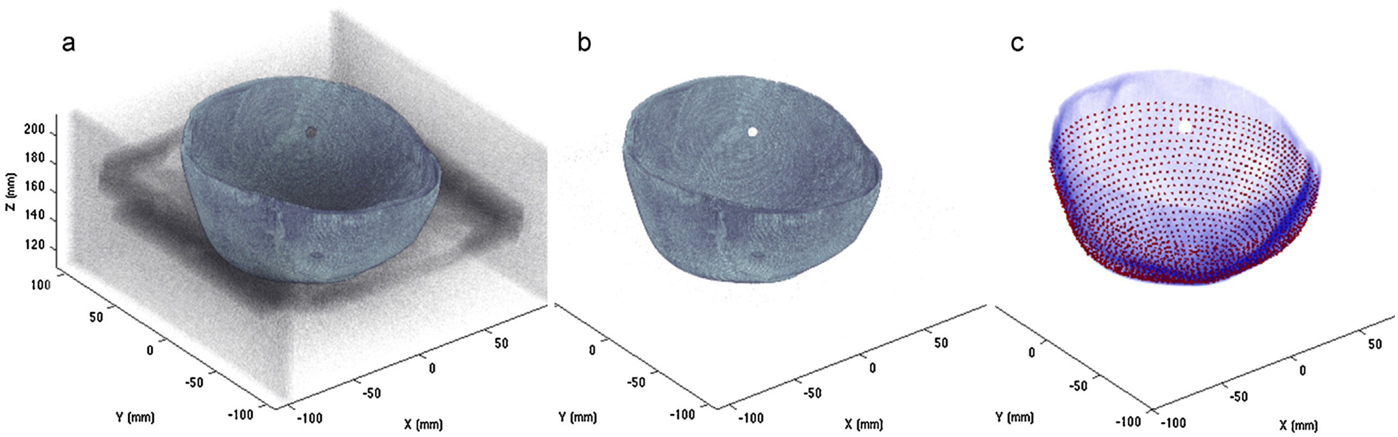

Fig. 1. Reconstructions of a representative calvarium, showing the progression from (a) the sterotactic frame used during CT imaging, (b) thresholding away of non-bone material, and (c) creation of measurement vectors and their location on the skull.

age and date of death, primary and contributing causes of death. The calvaria had been stored in a dry state, cleaned but without tissue fixation other than the initial embalming of the donated body. Prior to making measurements, these dessicated specimens were rehydrated in degassed water. Of the 51 calvaria studied, demographic and vital statistic information was available for 40 specimens. Of these, 26 were females ranging in age from 53 to 97 years at time of death, and 14 were males between 60 and 85 years at time of death.

2.2. Fixture and specimen chamber

The specimens were attached to acrylic stereotactic fixtures, for positioning within the CT scanner, and also to provide fiducial markers for coordinate transformation between the TcFUS and CT coordinate spaces. Prior to CT scanning, the skull specimen was placed in an acrylic vacuum chamber. The chamber with was then filled with deionized water, sealed, and placed under house vacuum (−300 mmHg) for a typical duration of three days to ensure complete skull degassing. Shorter degassing times have been reported using greater negative vacuum pressures [15].

2.3. CT imaging

After degassing, the chamber with skull was placed in the bore of the CT scanner (Discovery CT750 HD, GE Medical Systems, Waukesha, WI, USA) and scanned to create a set of transverse images. The CT image pixelation was 512×512, covering $320\,mm \times 320\,mm$ for pixel dimensions of 0.625 mm. The slice thickness was 0.625 mm, resulting in 0.625 mm cubic voxels. Each scan was done in helical mode, 120 kVP, with a boneplus reconstruction kernel (part of the GE software, which enhances bone edges and details).

2.4. Anatomical data analysis

The CT images were downloaded from the central PACS in DICOM format and imported into a local DICOM viewer (OsiriX, OsiriX Foundation, Geneva, Switzerland). In the viewer, the fiducial markers in the acrylic frame were located and their CT coordinates recorded. The DICOM images were read into MATLAB (The MathWorks Inc., Natick, MA, USA) to create 3D matrix of CT values, along with the voxel coordinates. All the CT datasets were aligned to the coordinate system of the TcFUS using the fiducials. The position of the calvarium in the acrylic frame and TcFUS coordinates is illustrated in Fig. 1a. For visualization purposes, all material other than bone could be thresholded away, shown in Fig. 1b.

2.5. Measurement vectors

A routine was then used to create the hemispherical arrangement of equispaced points around the calvarium. This hemisphere followed the convention of the TcFUS array with the bottom of the bowl located at the origin of the coordinate system. We chose to create a hemisphere of radius 180 mm and 2000 points, which placed the center of the hemisphere at (0,0,180) mm in TcFUS coordinates. This hemisphere and the calvarium were approximately concentric in the TcFUS reconstruction space. The points were then projected onto the outer surface of the calvarium by creating line segments extending from the hemisphere to the center point. These points are illustrated in Fig. 1c. The outer surface of the calvarium was easily identified, having a CT value much higher than the surrounding material (acrylic or water). The spatial coordinates of these points on the calvarium surface were then recorded. For each of these points, two neighboring points are found for a total of three points. These points form a small triangle, and the normal vector was found by vector cross-product. These normal vectors in turn were projected through the calvarium and CT values were interpolated onto them in increments of 0.25 mm (MATLAB interp3 function with linear interpolation). These values were then used to measure the skull thickness and radiological density at each of the 2000 sites. The CT values used for interpolation and measurement were analyzed without thresholding to prevent low-density regions in the skulls being set to zero and introducing an error to the density measurements.

2.6. Measurements of skull layers

Most regions of the calvarium consist of three distinct layers: the inner and outer cortical layers and the trabecular layer, or diploë, between the cortical layers. The diploë is absent near the sutures, which tend to be primarily cortical bone. However the majority of the measurement profiles allowed for the measurement of the three component layers. An algorithm was developed to identify the density maxima of both the inner and outer cortical layers and the intervening lower density values of the diploë. The outer boundaries of the cortical layers were defined as the points where the density values were equal to or greater than half of the associated cortical maximum, consistent with published recommendations [16–18]. The inner cortical boundaries were defined as the points where the density values were half of the difference between the cortical maximum and diploë minimum. The density profile across the diploë may be quite irregular, with several minima. The minimum closest to the respective cortical maximum was