

Localized Correction of Cortical Bone Geometry and X-Ray Intensity Information in Clinical CT Images

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Introduction

The capability to construct patient-specific finite element (FE) models to simulate the *in vivo* biomechanical environment of the skeleton holds great promise for the design of effective treatments for traumatic injuries, deformities, and numerous pathological conditions¹. The most feasible means of constructing such FE models relies on segmentation of cortical and trabecular bone structures in x-ray computed tomography (CT) images. To date, accuracy of the constructed models of complex bones such as the craniofacial skeleton (CFS) and pelvis have been limited by the resolution of clinical CT scanners. The primary structural features of these regions are cortical-trabecular shells, which exhibit sub-millimeter thickness. At these dimensions, the finite width of the scanner's point spread function (PSF), partial volume effects, and limited pixel size result in over-estimation of the thickness and under-estimation of intensity (density) measurements². This limitation in turn translates to severely erroneous geometrical and mechanical property assignment in the FE models³. This study presents a model-based automated method for estimation of cortical and trabecular bone thickness and intensity values at localized regions of shell bones based on clinical CT resolution data. In addition, a local PSF is produced, which can subsequently be used in deconvolution of the original CT data sets to restore the pixel intensity values prior to segmentation.

Materials and Methods

An algorithm is presented for estimating the true intensity profile of thin (<1.0mm thickness) and flat bone structures which exhibit a layer of trabecular bone in between thin bi-cortical bone layers. This implementation primarily exploits the x-ray attenuation and material density information inherent in clinical CT data sets, and models the overall result of limited pixel size, partial volume, and other blurring effects in high contrast areas by convolution of a rectangular function with a normalized Gaussian function. The rectangular function represents an idealized linear profile of CT values sampled perpendicular through the surface of the bone. This function is defined by six and three independent geometrical variables in the case of shell and thin bones respectively. An additional parameter (σ) determines the width for the Gaussian point spread function. To determine these variables, a non-linear optimization algorithm with an interior-point approach is employed subject to two constraints: 1) a linear equality function to maintain positive values of the geometrical entities in the profile, and 2) a non-linear function which equates the integral area of the rectangular function to that of the original CT line profile. The objective function of the optimization problem is the minimization of the fitting residual of the convolved rectangular function to the CT data. In addition, lower and upper bounds are defined in accordance with expected range of trabecular and cortical bone intensities, and the maximum expected overall thickness based on the extracted CT profile.

To validate the method, custom CT phantoms constructed from Teflon and Delrin were used, which exhibit HU value contrast in line with the expected intensities of cortical and trabecular bone. A combination of material thicknesses ranging from 0.25 to 2.36 mm were arranged within water-equivalent polymeric clamps to emulate structures of thin cortical bone (single layer Teflon) and shell bones (Teflon-Delrin-Teflon). The phantoms were imaged using a GE Lightspeed VCT scanner (0.23x0.23x0.625 voxel size). A cadaveric head was also imaged using this clinical CT system (0.48x0.48x0.625 voxel size). Micro-CT scans (Explore Locus, GE) of multiple excised regions of this head were also acquired, from which intensity and geometry values were taken to serve as gold standard measurements. Comparison between phantom/micro-CT image data were used to validate and evaluate the performance of this method.

Results

Based on the phantom and micro-CT data, the proposed method provides thickness estimates of thin cortical features (0.25 - 0.8mm

thick) to within 0.12 ± 0.07 mm of their true thickness (Figure 1). This compares to >1 mm thickness overestimation by using a full-width half-max threshold scheme for sub-millimeter thicknesses. The cortical/Teflon intensities estimated in the phantom samples was within 26 ± 36 HU, while the intensity in the original CT data was lower than true values by > 380 HU. Furthermore, the obtained value of σ for the Gaussian PSF is highly consistent between each scan performed at the same reconstruction resolution. This supports the hypothesis that the model captures the inherent blurring mechanism of the scanner, and may be employed by deblurring/deconvolution schemes to locally restore CT image data.

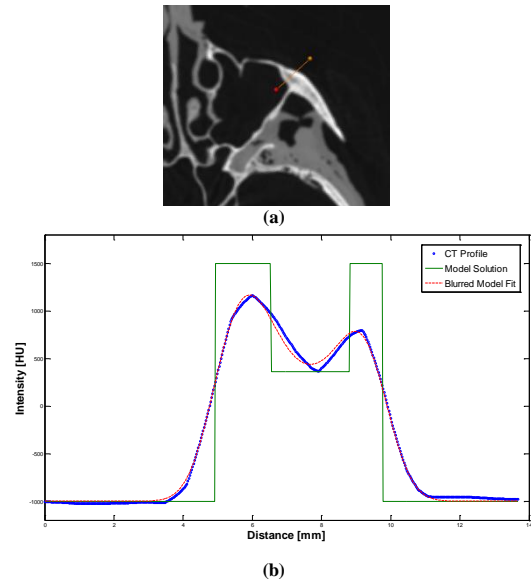


Figure 1. (a) A representative single line probe through a shell bone in the maxillary sinus region yielding a CT intensity profile (b) The original CT profile (blue), and the profile as obtained from the optimized fitting procedure performed by the method (red). The rectangular function (green) demonstrates the thickness and intensity estimates obtained by the model. Note that the cortical bone is thinner on the inner wall of the sinus.

Discussion and Conclusion

The presented method is a viable means of correcting for typically observed thickness overestimation and intensity underestimation of sub-millimeter cortical bone features. Its application provides a significant localized enhancement in resolution of CT values, which can be used to improve segmentation of CT images. This will have a direct impact on the accuracy of CT-based patient-specific FE models containing thin-bones, such as in the craniofacial skeleton, scapula and pelvis. In addition, modifications of the method can provide clinically relevant data regarding cortical shell volumes in any bone structure. Future work will extend this algorithm by its implementation as an interactive tool that applies the estimated PSF for global deblurring (deconvolution) of clinical CT data sets.

References

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