Estimating the Density of the Femoral Head Bone from Hip Resurfacing Patients using CT Scan Data

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INTRODUCTION: The success of orthopaedic surgical intervention is dependent on the quality of bone in the region of interest[1]. Bone is a non-homogeneous, anisotropic material. Osteoarthritis (OA) of the hip has an estimated prevalence of 12 percent in Canadian individuals aged twenty or older diagnosed with the disease and is characterized by changes in bone density[2]. Hip resurfacing arthroplasty (HRA) is a surgical intervention that replaces damaged exterior surfaces of the femoral head and relieves hip pain associated with OA[3]. Quantitative computed tomography (QCT) measures X-ray attenuation, facilitates the derivation of bone mineral density (BMD) and provides three-dimensional (3D) morphology. The aim of this study was to retrospectively estimate bone density of the femoral head of pre-operative HRA patients relative to the unaffected contralateral bone using homogeneous and inhomogeneous density estimation.

METHODS: Twenty-two pre-operative HRA patients' proximal femora were QCT scanned in GE Medical Systems Revolution HD (n=9) and LightSpeed Plus (n=13) scanners with a BONE reconstruction kernel, 120 kVp, and pixel size of 0.847 mm and 0.732 mm, respectively. QCT scans of the diseased and unaffected femoral head of each patient were segmented (Hounsfield Unit > 300) using Mimics v.24 (Materialise) to retain bone voxels and discard soft tissue voxels. Mean CT number and standard deviation were recorded for each mask. Hounsfield units (HU) were calibrated to bone density: a custom phantom of four hydroxyapatite standards (CIRS Inc, Norfolk, VA) that encompass the apparent densities typical of human femoral trabecular and cortical bone previously scanned in GE Medical Systems Revolution HD and LightSpeed Plus with the same reconstruction kernel and voltage were used to create calibration equations relating CT number to bone density following American Medical Society standards[4,5] (Eq 1, Eq 2).

$$\rho_{CT,\text{Revolution HD}} = 1.33 * HU - 6.51 \quad (1) \quad \rho_{CT,\text{LightSpeed Plus}} = 1.36 * HU + 5.25 \quad (2) \quad \rho_{app} = 0.983 * \rho_{CT} + 13.2 \quad (3)[1]$$

The homogeneous density of femoral head trabecular bone was estimated using Mimics segmented QCT scans [Figure 1A]. The mean CT number of the diseased and unaffected femoral head were converted to homogeneous apparent density using calibration equations (Eq 1 and 2) and empirical relationships from literature (Eq 3)[1]. The inhomogeneous density of femoral head trabecular bone was estimated from a finite element mesh (Abaqus 2017) with density assigned to each element using a custom-made MATLAB algorithm that converts HU from the QCT scan into density using calibration phantom equations (Eq 1 and 2) and empirical relationships from the literature (Eq 3) [1] [Figure 1B].
Before statistical analysis was conducted, normality of hip head density for each patient was examined with skewness and kurtosis. Non-parametric statistical tests were performed on all data. The Mann-Whitney U test ($\alpha = 0.05$) tested statistical difference between: (I) homogeneous and inhomogeneous density estimation; and (II) the diseased versus the unaffected femoral head density for the diseased and unaffected groups. To evaluate partial volume effect, Friedman's ANOVA test ($\alpha = 0.05$) was used to determine if the size of inhomogeneous elements created a statistical difference in femoral head density distribution for five cases.

RESULTS: Homogeneous density estimation was statistically different than inhomogeneous density estimation for the diseased ($p < 0.0001$) and unaffected ($p < 0.0001$) femoral heads [Figure 1C]. There was no statistical difference between diseased group femoral head homogeneous density estimation and unaffected group femoral head homogeneous density estimation ($p = 0.954$) or between diseased group femoral head inhomogeneous density estimation and unaffected group inhomogeneous femoral head density estimation ($p = 0.958$). There was not a statistical difference between element size and the inhomogeneous estimated density distribution for five of twenty-two patients tested ($p_{\bar{x}} = 0.604$) [Figure 1D].

DISCUSSION: The inhomogeneous estimated density distribution of the diseased and unaffected femoral heads is consistent with recent literature (98-250 mg/cc)[1,6]. Statistical tests did not find a difference in inhomogeneous density due to element size, thus indicating that density estimation from voxel HU value was not sensitive to element size. It should be noted that density estimation could not be validated as this was a retrospective study. Further, partial volume error caused by QCT scanner resolution limits could have affected estimated density in the cortical and trabecular transition region, giving density estimations with higher error.

CLINICAL RELEVANCE: This study demonstrated the application of density estimation techniques to quantify bone quality for pre-operative HRA patients. Quantifying bone density can be used to aid clinicians in pre-operative planning and post-operative follow-up of orthopaedic interventions like HRA.

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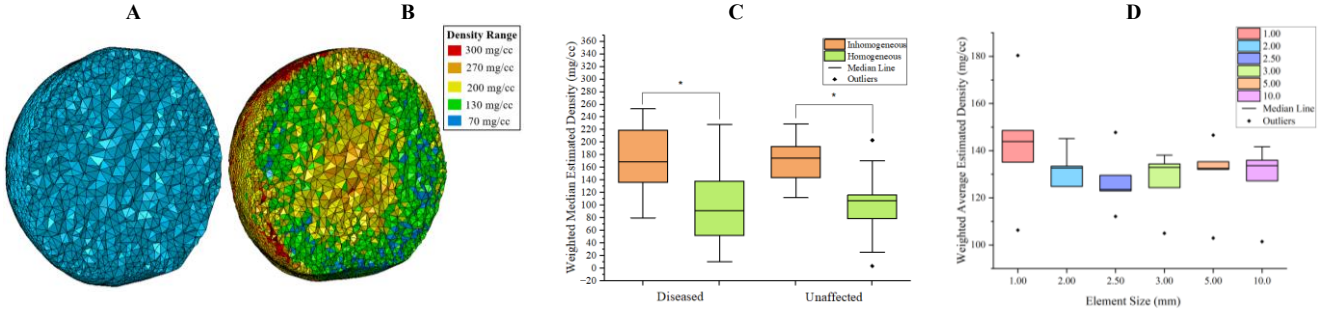

Figure 1: A) Median CT number homogeneous density distribution. B) Inhomogeneous patient specific density distribution. C) Inhomogeneous (orange) versus homogeneous (green) median estimated density (mg/cc) for diseased and unaffected femoral heads. D) Element size (mm) and relation to weighted average estimated density (mg/cc).