Interskeletal Variation of Bone Mineral Density, Geometry and Microstructure in Long Bone Shafts under Habitual Loading

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Introduction: Bipedal locomotion in human relies on the lower limbs to transport and support the trunk during the habitual gait loading. The greatest loading on the bone comes from the muscle force. Electromyographic analyses of gait show that lower limb muscles are active in different phases of gait cycle to meet the demand of changing body vector, whereas the upper limbs, without significant muscle activity, are secondary in function that it serves to balance the body movement during the locomotion1. Thus, the upper and lower limbs are subjected to different mechanical milieu under earth gravity during habitual gait loading. It is hypothesized that there is differential bone adaptation between tibia and radius in bone quantity and bone quality under long-term habitual loading. The aim of the investigation was to study bone quantity and bone quality of tibia and radius under such mechanical influence with elderly cadavers using a multi-modality imaging approach.

Materials and Methods: Twenty embalmed cadavers of Chinese ethnicity were used. They consisted of 2 females and 18 males aged 70.8 ± 8.5 without history of metabolic diseases and macroscopic bone deformities. A Tibia and a Radius were harvested from individual cadavers, for a total of 16 left tibiae, 4 right tibiae and 20 left radii. The cortical bone mineral density (cBMD) of the distal radius and tibia were measured using a highly accurate multi-slice pQCT (Densiscan 2000, Scanco Medical, Bassersdorf, Switzerland). The ex vivo imaging protocol was the same as in vivo pQCT applications as detailed in Ruegsegger2. Also, both the polar moment of inertia (PMI) and thickness of cortical bone at the distal radius and tibia were derived from the tomographic images. Two bone slices corresponding to the pQCT standardized scan location in the distal tibia and radius were cut perpendicular to the long axis of bone shaft using saw microtome. One slice was prepared for backscattered electron (BSE) imaging and the other for circularly polarised light (CPL) microscopy to quantify the degree of mineralization with weighted mean grayscale (WMGL) and collagen fibre orientation with collagen fibre orientation (CFO) index, respectively. The backscattered image was also used to study the osteon morphology. In each of the imaging evaluation, measurements taken at the anterior, posterior, medial and lateral cortices were pooled for comparative studies between radius and tibia.

Results: Table 1 summarises the imaging evaluation of bone quantity and bone quality between radius and tibia. pQCT measurements showed that radius had significantly 8.1% greater cBMD at tissue level excluding the bone marrow cavity, than the tibia. At organ level including the bone marrow cavity, the radius had significantly 35.4% higher cBMD than the tibia. It also showed that the tibia had a significant 26.1% greater cortical thickness than the radius. A BSE measurement demonstrated that the distal radius had, on average, a significant 2.8% greater degree of mineralisation in terms of WMGL than the distal tibia. With regard to collagen fibre orientation, the tibia had a significant 17.3% greater CFO index than the radius. This means that the collagens in tibia are in a relatively more transverse-to-oblique direction with respect to the long axis of the bone compared to radius. With regard to osteon morphology, the tibia had a significant 11.2% larger OA and 5.4% greater ODia than the radius. The HCA of the distal tibia was a significant 55.6% greater than the distal radius. The % IP, contributed by both Haversian canal porosity and other porous structures, of the tibia had a significant 23.2% higher level of intracortical porosity than the radius. There were no significant differences in OCA, ODen, % FASB, and %FAIB between the tibia and radius.

Discussion: The findings demonstrated that porosities from the Haversian canals and other pores accounted mainly to the difference in cBMD compared to the degree of mineralisation. The relative large porosities and reduced degree of mineralisation seen in the tibia may be due to the differential bone remodelling rates between the tibia and radius1. The tibia, being subject to habitual dynamic compressive loading as compared to the non-weight-bearing nature of the radius, may activate a higher remodelling rate, which does not allow full secondary mineralisation. The higher remodelling rate may be evident with the findings that the tibia has shown a tendency to have a 4% higher osteon density and a 8.5% greater % FASB compared to radius. Being subject to habitual dynamic loading, these physiologic strains may produce more microdamage in the tibia cortices. Thus, the bone activates a higher remodelling rate to remove the damage, resulting in lower mineralisation and higher porosities seen in the tibial cortex. To couple with the lower cBMD in the tibia, it exhibited a geometric adaptation with an increase of 26% and 8 times greater in cortical thickness and PMI, respectively. Also, the tibia showed significantly lower mineralisation along with more transverse to oblique collagen fibre orientation. It is argued that the increased remodelling rate in the cortex of horse radius, subject to compression, was associated with the development of less longitudinal orientation of collagen fibres in the secondary osteons4. In the present study, the synergy brought about by an increase in cortical thickness, PMI, and the CFO index in tibia, coupling with the lower mineralisation may enhance the resistance in bend and compression loading of the lower leg during walking. Also, the lower cBMD in tibia compared to radius may save the long-term energy cost in acceleration.

References:

Table 1 summarises the imaging evaluation of bone quantity and bone quality under long-term habitual loading.