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ORIGINAL ARTICLE

Three-dimensional morphometric properties of rod- and plate-like trabeculae in adolescent cancellous bone

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Volumetric spatial decomposition

Abstarct This study included 23 normal human proximal tibiae. These tibiae were divided into three groups: adolescents (9–17 years, n = 6), young adults (18–24 years, n = 9) and adults (25–30 years, n = 8). From each tibia, six cubic cancellous bone samples (dimensions $8 \times 8 \times 8\,mm^3$) were sawed from each medial and lateral condyle, yielding a total of 276 samples. These samples were scanned using microcomputed tomography leading to three-dimensional cubic voxel sizes of $10.5 \times 10.5 \times 10.5\,\mu m^3$. The morphometric parameters of individual rod- and plate-like trabeculae were calculated and compared among three age groups. Significant differences in some morphometric parameters were revealed. The mean longitudinal length of rods was significantly greater in the adolescents than in the young adults. Plate volume density showed an increasing trend with age, although not significant. Plate-like trabeculae were more in the medial condyle of adolescents than in the lateral condyle and changed towards more plate-like trabeculae in the adults. The single best predictor for the mechanical properties was apparent density. Apparent density alone explained 59% variations in Young's modulus, 77% in ultimate stress and 34% in failure energy, respectively (all $p < 0.01$). Morphometric parameters might improve this prediction. In conclusion, this study has reported for the first time the morphometric parameters of rod- and plate-like trabeculae in adolescent proximal tibial cancellous bone, which will improve our understanding of morphometric changes in individual trabeculae during development and growth. Furthermore, separate analysis of individual rods and plates may also help reveal disease-related morphometric changes beyond bone mineral density. The translational potential of this article is that a thorough quantification of individual

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trabeculae during development and growth may help understand disease-related three-dimensional morphometric changes beyond bone mineral density.

Introduction

Three-dimensional (3D) microarchitectural, mechanical, collagen and mineral properties of normal adolescent cancellous bone have been investigated to obtain more insight into the subchondral bone adaptations during development and growth [1]. Microcomputed tomography (micro-CT) imaging with high spatial resolution has enabled a global analysis of the sophisticated 3D microarchitecture of cancellous bone describing the average structure for the whole bone specimen in an unbiased and assumption-free manner. Specifically, model-independent measures of the trabecular microarchitecture such as volume fraction, connectivity density (ConnD), degree of anisotropy, trabecular thickness (TbTh), separation, surface density and type of the structure (rod or plate) have been standardized and routinized for the study of cancellous bone and provided a strong tool and new insights into the transformation of cancellous bone structure in diseases [2,3]. These investigations have revealed subchondral bone changes in proximal tibiae from development and growth to ageing [1,2] and disease-related changes such as osteoporosis [4], osteoarthritis [5,6], or diabetes [5].

With further advance of imaging techniques in recent years, the developments in software for micro-CT data sets have achieved the ability to analyse individual trabecular elements separately [7]. Volumetric spatial decomposition (VSD) of trabeculae, developed by Stauber and Müller [7], has enabled measurements of trabecular bone samples into its basic elements (rods and plates), which is a framework for the element-based description of bone morphometry. This technique has been applied to human cancellous bones from spinal column [8,9] and femoral heads [9]. The 3D microarchitecture and morphometry of rod- and plate-like trabeculae were quantified and related to Young's moduli as assessed by the experimental uniaxial compression test and computational finite element analysis [8]. It is concluded that the individual morphometry of rod- and plate-like trabeculae helps improving our understanding of the relative importance of structural changes in the determination of the stiffness of bone.

The combination of morphometric parameters of rod- and plate-like trabeculae and 3D microarchitecture is a useful tool for a detailed and quantitative description of age- and disease-related changes in the bone microarchitecture [9–11]. This methodology has enabled to show age-related and site differences in measures of individual trabeculae that may improve the understanding of the site-specific role of the bone microarchitecture in determining bone quality [8].

We have recently reported global microarchitectural properties of normal human adolescent cancellous bone and their physical properties, collagen and mineral and mechanical properties [1]. This study has revealed that adolescent cancellous bone has similar bone volume fraction, structure type and connectivity, and significantly lower tissue density, bone surface density and mineral concentration but higher collagen concentration than in the young adult and adult cancellous bones [1]. However, the morphometric properties of rod- and plate-like trabeculae in adolescent cancellous bone have not yet been investigated.

Thus, the aims of this study were to investigate 3D morphometric properties of rod- and plate-like trabeculae in normal adolescent cancellous bone and to compare them with adult cancellous bones to reveal morphometric changes from adolescence to adult life to obtain more insight into the subchondral bone adaptations during development and growth. We further evaluated the associations between the morphometric properties of rod- and plate-like trabeculae and their mechanical properties, and determined the best predictors for mechanical properties from the measured morphometric parameters, together with the 3D microarchitectural parameters and physical and compositional properties (i.e., densities, mineral and collagen concentrations) in a study [1], thus providing more insight into the adolescent bone microarchitecture and its role in determining mechanical properties. This investigation will improve our understanding of morphometric changes in individual rod- and plate-like trabeculae during development and growth. Prospectively, it may also help predict disease-related morphometric changes, such as osteoporosis-related fractures beyond bone mineral density, and effects of pharmaceutical intervention and osteoarthritis-related microdamages of subchondral bone.

We hypothesized that local morphometric parameters of the adolescent cancellous bone might be significantly different from those of adult cancellous bones, and the combination of 3D microarchitectural properties and morphometric parameters of individual rod- and plate-like trabeculae could improve the prediction of mechanical properties.

Materials and methods

The materials used in this study have been described in detail by Ding et al [1]. Briefly, human left proximal tibiae were collected from 23 donors with mean age 21 years (9–30 years). All these donors were Caucasians, and 5 were females and 18 were males. A criterion for sample selection was strictly controlled [12], i.e., these donors had all died suddenly from either traumatic or acute disease. No history of musculoskeletal diseases was recorded. They had always been active physically and had no more than 2 weeks of

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