The Development of Bone Strength at the Proximal Radius during Childhood and Adolescence

E. SCHOENAU, C. M. NEU, F. RAUCH, AND F. MANZ

Children’s Hospital, University of Cologne (E.S., C.M.N., F.R.), D-50924 Cologne; and Research Institute of Child Nutrition (C.M.N., F.M.), D-44225 Dortmund, Germany

ABSTRACT

Current investigations of bone development mostly focus on bone mass, but bone strength may be functionally more important than mass. Therefore, we compared the developmental changes in cortical bone mass (BMCcort) and parameters of cortical bone strength [polar moment of inertia, section modulus, and strength strain index (SSI)]. Analyses were performed at the 65% site of the proximal radius using peripheral quantitative computed tomography. The study population comprised 469 healthy subjects, 6–40 yr of age (273 females). Both in prepubertal children (pubertal stage 1) and after puberty (pubertal stage 5 and adults) all studied parameters were significantly higher in males. During puberty (pubertal stages 2–4) the gender-specific differences were generally somewhat smaller. All of the measured parameters increased significantly with age and pubertal stage. However, although the percent increase in BMCcort between the youngest children and adults was similar between the genders, the increases in polar moment of inertia, section modulus, and SSI were higher in males. The ratio between section modulus and BMCcort was consistently higher in males after the age of 11 yr and after pubertal stage 2. Similar results were found for ratios between polar moment of inertia or SSI and BMCcort. These results show that for a given bone mass, males have stronger bones than females after pubertal stage 2. This reflects the fact that in puberty males add bone mostly on the periosteal surface, where the effect on bone strength is highest, whereas females add bone on the endocortical surface, which has a smaller effect on bone stability. The purpose of the mechanically inefficient endocortical apposition in female puberty might be to create a reservoir of calcium for future pregnancy and lactation. (J Clin Endocrinol Metab 86: 613–618, 2001)

IN THE CURRENT literature bone development is commonly described as a process of bone mineral accretion, which eventually leads to the accumulation of peak bone mass. This focus on bone mass probably reflects the ease with which this parameter can be measured using widely available densitometric techniques. However, describing bone development simply in terms of bone mass changes veils the fact that the key issue of bone development is to make bones stronger rather than heavier (1). In fact, if maximizing bone mass in itself carried an important functional advantage for the individual, the evolutionary process should have led to the formation of bones with solid, not hollow, diaphyses. As it is, the anatomical features of bones suggest that bone development is set to attain peak bone strength by using as little material as possible.

Obviously, for a bone of a given anatomical structure, mass generally correlates with strength. However, a given amount of material will influence the strength of a structure differently depending on where it is located. Architectural parameters have been devised that allow calculation of the strength of a structure from the amount and distribution of the raw material. Such size and shape parameters include the polar moment of inertia and the section modulus (2, 3).

The polar moment of inertia is a measure of the distribution of material around the center of a specimen (Fig. 1). The shear stress created in a bone by torque is inversely related to the polar moment of inertia (2). Thus, in a bone with a higher polar moment of inertia the same torque will result in smaller shear stress than in a bone with a lower polar moment of inertia. The section modulus is a closely related parameter (Fig. 1) that indicates the resistance of a bone to stress. A higher section modulus, therefore, means that mechanical failure occurs at higher loads (4).

These architectural parameters have long been used in bone biomechanical studies and have been found to be as good indicators of the strength of bones as they are for engineering purposes (1–3, 5). Algorithms have been developed to assess polar moment of inertia and section modulus with techniques such as single or dual energy photon absorptiometry (5–7). However, some prior assumptions on bone shape have to be made, which may introduce some error. It is one of the advantages of peripheral quantitative computed tomography (pQCT) that these architectural parameters can be easily and precisely determined (8).

In addition to the size and shape factors mentioned above, the strength of a bone as an organ depends on the material properties of bone as a tissue (4). A key material property is the elastic modulus, or stiffness (2). It is difficult to measure stiffness directly in vivo, as invasive testing is required. However, volumetric bone mineral density (BMD) of cortical bone in the narrow physiological range has an approximately linear relationship with elastic modulus (4) and can be determined by pQCT.

Thus, pQCT allows assessment of both architectural and material components of bone strength. Combining both types of indexes should allow close estimates of bone strength (4). In fact, the product of volumetric cortical BMD and cross-sectional moment of inertia is closely associated with rat femur bending strength (9). A similar parameter, the strength strain index (SSI), has been developed by Schiessl et al. (Fig. 1) (10). This is calculated as the product of

Received July 21, 2000. Revision received October 24, 2000. Accepted October 26, 2000.

Address all correspondence and requests for reprints to: Dr. Eckhard Schoenau, Children’s Hospital, University of Cologne, Joseph Stelzmann Strasse 9, D-50924 Cologne, Germany.
section modulus and volumetric cortical BMD normalized to the maximal physiological cortical BMD of human bones (11). The SSI has been shown to provide a good estimate of the mechanical strength of human radii (12).

In this study we performed pQCT analyses at the proximal radial diaphysis in children, adolescents, and young adults to examine the developmental variations in polar moment of inertia, section modulus, and SSI. This should allow evaluation of the development of bone strength at the proximal radius. In addition, we investigated the relationship between bone mass and architectural parameters of bone stability during bone development.

Subjects and Methods

The study population comprised 371 healthy children and adolescents as well as those parents who were below 40 yr of age (n = 107; 19 men and 88 women; aged 29–40 yr). Five children had to be excluded from the present analysis because of motion artifacts during the measurement run. The results from 4 boys were excluded because a significant amount of trabeculized cortex interfered with the analysis of cortical bone. Thus, 362 children and adolescents (177 males and 185 females) were included in the following evaluation. The children were participants in the DONALD (Dortmund Nutritional and Anthropometric Longitudinally Designed) study, an ongoing observational study investigating the interrelations of nutrition, growth, and metabolism in healthy children. This study is performed at the Research Institute for Child Nutrition in Dortmund, Germany. The cohort was initially recruited through personal contacts of collaborators of the Research Institute and later through personal recommendation of parents whose children were already participating. Overall, the study population mostly comprised middle class families, and all participants were of Caucasian origin. On an annual basis, all participants in this study undergo a full medical history and examination starting in infancy. Peripheral QCT analysis was performed once in each participant on the occasion of a yearly check-up.

The stage of sexual development was determined by physical examination using the grading system defined by Tanner for public hair. Assessment of pubertal stage was refused by 26 boys and 27 girls. Forearm length was measured at the nondominant forearm as the distance between the ulnar styloid process and the olecranon using a caliper.

Informed consent was obtained from the children’s parents or from subjects more than 18 yr old. In addition, written assent was also obtained from subjects between 14–17 yr of age. The study protocol was approved by the ethics committee of the University of Cologne and the Bundesamt für Strahlenschutz (Federal Agency for Protection from Radiation, Salzgitter, Germany).

pQCT

pQCT analysis was performed at the nondominant forearm using a technology (XCT 2000, Stratec, Inc., Pforzheim, Germany) described previously (13). The scanner was positioned at the site of the radius whose distance to the distal radial articular cartilage corresponded to 65% of the ulnar length. A 2-mm-thick single tomographic slice was taken at a voxel size of 0.4 mm. Image processing and calculation of numerical values were performed using the manufacturer’s software package (version 5.40, Stratec, Inc.).

For all analyses except the determination of SSI, cortical bone was identified at a threshold of 710 mg/cm³. To assess SSI, a threshold of 480 mg/cm³ was used according to the default settings of the manufacturer’s software. This choice of thresholds is based on technical considerations regarding the partial volume effect, which is a source of error in QCT (14). Partial volume effect refers to measurement errors caused by voxels that are only partially filled with mineralized bone. By choosing a threshold of 710 mg/cm³ (which is about midway between the densities of fully mineralized bone and soft tissue), about as many voxels that are only partially filled with cortical bone will be included in the analysis as will be excluded. Thus, the error due to the partial volume effect will be minimized. In the analysis of SSI, the partial volume effect plays a smaller role, because the individual density reading of each voxel is used for the calculation (Fig. 1).

FIG. 1. Definitions of polar moment of inertia, section modulus, and SSI. A schematic view of a bone’s cross-section is shown. In the formulae, A is the cross-sectional area of a voxel (in this study 0.4 × 0.4 mm = 0.16 mm²), d is the distance of the voxel from the center of gravity, \( vBMD_{\text{vox}} \) is the volumetric bone mineral density in the voxel (milligrams per cm³), \( d_{\text{max}} \) is the maximum distance of any of the voxels of the cortical cross-section from the center of gravity, and \( vBMD_{\text{max}} \) is the maximum mineral density of human bone under physiological conditions. This corresponds to the mineral density of cortical bone adjusted for porosity on the light microscopic level. \( vBMD_{\text{max}} \) was set at 1200 mg/cm³ (11).

FIG. 2. Age dependency of cortical bone mineral content in females (left) and males (right). Results in adults from 29–40 yr of age are indicated as bars (mean ± 2 sd).
Therefore, a lower threshold can be used, which should allow a more accurate analysis of the bone’s geometry. Cortical bone mineral content (BMCcort) represents the mass of mineral in a 1-mm-thick slice of the cortical bone’s cross-section. Polar moment of inertia, section modulus, and SSI were calculated as indicated in Fig. 1.

Statistical analyses

For comparisons between two groups, U tests were used. The significance of differences between more than two groups was calculated by the Kruskal-Wallis test. For these calculations SAS 6.12 software package (SAS Institute, Inc., Cary, NC) was used.

Results

Figures 2 and 3 display the variation with age in BMCcort and in parameters of cortical architecture. The mean and sd of these age-dependent results are shown in Tables 1 and 2; the variations with pubertal stage are given in Tables 3 and 4. All of the measured parameters increased significantly with age and pubertal stage. BMCcort was higher in males in the youngest age groups and after the age of 15 yr. Moment of inertia, section modulus, and SSI tended to be higher in males in all age groups, but the difference in females was significant only in the 8–9 yr age group and after age 15 yr. Both in prepubertal children (pubertal stage 1) and after puberty (pubertal stage 5) all studied parameters were significantly higher in males. During puberty (pubertal stage 2–4) the gender-specific differences were generally somewhat smaller.

Between the age of 6–7 yr and adulthood, the relative increase in BMCcort was similar between the genders (197% in females, 200% in males). However, the relative increases in polar moment of inertia, section modulus, and SSI were higher in males. We therefore evaluated the developmental changes in the ratio between these architectural parameters and BMCcort. As shown in Fig. 4, the ratio between section modulus and BMCcort was consistently higher in males after the age of 11 yr and after pubertal stage 2. Similar results were found for polar moment of inertia and SSI (data not shown).

![Fig. 3. Age dependency of parameters of cortical architecture in females (left) and males (right). Results in adults from 29–40 yr of age are indicated as bars (mean ± 2 sd).](image-url)
Dependency of cortical bone mass and architectural parameters on pubertal stage in males

Table 4 shows the interrelationship between bone mass and architectural parameters. For both genders, indexes of architecture were highly interrelated, with correlation coefficients of 0.98 and 0.99. The association between these parameters and BMCcort was slightly less close.

Discussion

In this study we describe the normal development of cortical bone mass and architectural indexes of bone strength at the proximal radius. The study population comprised children and adolescents as well as their parents, and thus these...
two groups are not independent. This may introduce some bias when the children and adolescents group is compared with the adult cohort, but should not influence the analysis of age- and gender-related changes in the children and adolescents group, which was the main focus of this study.

According to the classical work of Garn et al., the development of cortical bone takes a gender-specific course (15). Before puberty the cortices of girls and boys undergo periosteal expansion and endocortical resorption. However, during puberty endocortical apposition occurs in girls, but not in boys. Endocortical apposition during female puberty is a well documented phenomenon, which was also found in studies on the midradius (16) and the femoral shaft (17). Periosteal expansion proceeds longer in boys than in girls, leading to a larger external bone size in men than in women (15). We have previously shown that this general pattern can also be observed at the 65% site of the proximal radius (13).

In subjects without bone disease, volumetric bone mineral density in the cortex changes very little (a few percentage points) between the age of 6 yr and adulthood (18, 19). Therefore, SSI is mostly determined by the section modulus, which increased by about 300–400% in the current study. As shown by the close interrelationship between SSI and the parameters of bone architecture, these indexes basically provided redundant information in the present study. However, this may be different in disorders with abnormal intracortical porosity or mineralization, such as osteoporosis or osteomalacia.

The absolute values for parameters of bone stability were higher in males than in females. This is not a surprising finding, as it is well known that men have stronger bones than women, which is commonly attributed to higher bone mass in men. This gender difference in bone mass was also obvious in the present study. However, we found higher ratios between architectural parameters and BMCcort in postpubertal males compared with females. This means that for a given cortical bone mass, males have stronger bones than females due to differences in bone mass distribution (Fig. 5). The reason for this difference is that in puberty males add bone to the periosteal surface, where the effect on bone strength is highest. In contrast, females add bone to the endocortical surface, where it has a relatively small effect on bone stability. Thus, pubertal bone development in males appears to be more efficient with regard to attaining maximal bone strength by using as little material as possible.

What, then, might be the purpose of the mechanically inefficient endocortical apposition of bone during female puberty? As puberty is the time of sexual maturation, it appears appropriate to interpret the corresponding changes as a preparation for reproductive functions. During pregnancy and lactation women have to transfer a large amount of calcium to their fetus/newborn (20). To achieve this calcium transfer, women lose a substantial amount of bone, notably during the period of lactation (20). In that perspective it makes sense that female puberty is associated with the accumulation of bone that is of little mechanical value. A reservoir of calcium is created that can be tapped during later periods of lactation without compromising bone stability.

![Fig. 4](image-url) Dependency of the ratio between section modulus and cortical bone mineral content on age and pubertal stage. The significance of the difference between genders is indicated for each age group: *, P < 0.05; **, P < 0.01; ***, P < 0.001.

![Fig. 5](image-url) Schematic representation of the effect of bone cross-sectional geometry on parameters of bone stability. The right and the left bone cross-sections have the same cortical area, and thus cortical bone mass is identical. However, the external diameter is greater in the right bone. For this reason, polar moment of inertia and section modulus are considerably higher.

<table>
<thead>
<tr>
<th>Table 5. Pearson's correlation coefficients between cortical bone mass and architectural parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSI</strong></td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Female</td>
</tr>
<tr>
<td>BMCcort</td>
</tr>
<tr>
<td>Polar moment of inertia</td>
</tr>
<tr>
<td>Section modulus</td>
</tr>
<tr>
<td>Male</td>
</tr>
<tr>
<td>BMCcort</td>
</tr>
<tr>
<td>Polar moment of inertia</td>
</tr>
<tr>
<td>Section modulus</td>
</tr>
</tbody>
</table>

All correlations are statistically significant (P << 0.0001).
Acknowledgments

The technical support of Stratec, Inc., is gratefully acknowledged. We are indebted to the entire staff of the Research Institute for Child Nutrition for continuing support.

References