Normal Vertebral Body Size and Compressive Strength: Relations to Age and to Vertebral and Iliac Trabecular Bone Compressive Strength

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Abstract

Three thoracic (T1-T7) and three lumbar (L1-L3) vertebral bodies and the anterior parts of both iliac crests were removed from 44 normal individuals aged 15–87 years who had died suddenly. Small, cylindrical samples of trabecular bone (length 5 mm, diameter 7 mm) from T6, L1, and L2 and from the standard site for iliac crest biopsies were compressed in an Alwetron-250 materials testing machine. Whole vertebral bodies from T6, T7, and L2 with cut planoparallel end-plates were compressed in an Instron materials testing machine. The maximum compressive stress value $\sigma_{\text{max}}$ of the whole vertebral bodies and of the vertical vertebral trabecular bone decreased with age with almost parallel linear regression lines. At any age the $\sigma_{\text{max}}$ for whole vertebral bodies was about 1.6 MPa (1 MPa = 100 N/cm²) higher than for the trabecular bone. The average cross-sectional area of the vertebral bodies increased by 25–30% from the age of 20 to 80 years. The anisotropic properties of the vertebral trabecular bone (expressed as the ratio between the vertical and horizontal $\sigma_{\text{max}}$) increased markedly with age. A highly significant positive correlation was observed between the vertical vertebral trabecular bone $\sigma_{\text{max}}(x)$ and the total vertebral body $\sigma_{\text{max}}(y = 0.90x + 1.75, r = 0.88, P < 0.01)$. The slope was not significantly different from 1, whereas the intercept was positive ($P < 0.01$). The average total vertebral body $\sigma_{\text{max}}$ (range 1.5–7.8 MPa) could be predicted from mechanical tests on horizontal iliac crest bone biopsies with an error (SEE, standard error of estimate) of 0.92 MPa.

Key Words: Vertebral Bodies–Trabecular Bone–Compressive Strength–Anisotropy–Aging.

Introduction

We have previously demonstrated that the maximum compressive stress [$\sigma_{\text{max}}, \text{MPa}$ (1 MPa = 100 N/cm²)] of both vertebral and iliac trabecular bone decreases with age in normal individuals (Mosekilde et al., 1985). The anisotropy index, expressed as the ratio between the vertical and the horizontal $\sigma_{\text{max}}$, is unchanged with age in the nonload-bearing iliac trabecular bone but increases with age in the loadbearing vertebral trabecular bone. In spite of these contrasting anisotropic properties we found that the vertical $\sigma_{\text{max}}$ of vertebral trabecular bone (range 0.4–6.5 MPa) could be predicted from horizontal mechanical tests on iliac crest trabecular bone with an error (SEE, standard error of estimate) of 0.90 MPa.

The anisotropy of the weightbearing vertebral trabecular bone is accentuated with age because of a loss of thin horizontal trabeculae and an increase in diameter among the remaining vertical trabeculae (Saville, 1967; Atkinson, 1967; Parfitt, 1984). These changes in the internal architecture of the vertebral bodies might mitigate the effect on bone strength of the age-related bone loss. It is, however, not only the internal architecture of the vertebral bodies that changes with age. It has been shown by measurements on x-ray images of thin bone sections from vertebral bodies that the diameter of the vertebral bodies increases with age by continuous periosteal growth (Pesch et al., 1980). This increase in cross-sectional area of the loadbearing vertebral body could, as suggested by Mazess (1982) and Parfitt (1984), be a prime factor in counteracting the steady fall in bone mass and in trabecular bone compressive strength with increasing age.

The aim of the present study was to describe the age-dependent variations in whole vertebral body compressive strength, vertebral trabecular bone compressive strength,
and vertebral body size in material from 44 normal individuals to obtain information about the relative contribution of trabecular and cortical bone to the age-dependent variations in the total compressive strength of the vertebral bodies. Furthermore, the error of predicting whole vertebral body compressive strength from horizontal mechanical tests on iliac crest trabecular bone (the normal site for iliac crest bone biopsies) was investigated.

Materials and Methods

The study comprised 44 normal individuals, 27 females and 17 males, aged 15–87 years (mean 58 years). All had died in accidents or from acute diseases without prior periods of immobility. None of the subjects had suffered osteoporotic fractures, and x-rays of the removed vertebral bodies and iliac crests showed no pathological change. Three thoracic vertebral bodies (T1–T3), three lumbar vertebral bodies (L1–L3), and the anterior part of the right and left iliac crests were frozen at -20°C immediately after removal. Cylindrical bone samples (diameter 7 mm) were obtained by drilling the frozen bone from the iliac crest in the horizontal direction in an area 2 cm below the edge of the iliac crest and 2–4 cm behind the anterior, superior iliac spine, imitating a normal iliac crest bone biopsy (Pao, 1983). From the central part of the vertebral bodies of T1, L1, and L3, vertical and horizontal samples were taken in the same way. The specimens were sawn carefully, using a special device for fixation (Mosekilde et al., 1985), to obtain planoparallel ends and an exact length of 5 mm. This procedure removed the cortical bone from the iliac crest bone specimens. The bone specimens were then slowly thawed to +20°C and placed in Ringer’s solution for 30 min before testing in an Instron-250 materials testing machine at a constant compression rate of 2 mm/min. The samples were placed unsupported in the testing machine, and small variations in the position of the end-plates of the cylinders during compression were corrected for by an interposed steel ball-holding.

The remaining vertebral bodies, T1, T2, and L3 were sawed 2 mm below their end-plates to obtain exact planoparallel surfaces for the compression test. By this procedure the nonloadbearing exostoses were removed, and the vertebral bodies comprised only the central ring surrounding the central trabecular core. The vertebral bodies were then thawed to +20°C and placed in Ringer’s solution. The volume of the vertebral bodies was measured by weighing the water displaced when the specimens were kept free-floating in water. The height of the vertebral bodies was measured with a micrometer, and the mean cross-sectional area was expressed as the volume divided by the height. The vertebral bodies were compressed using an Instron materials testing machine at a constant rate of 4.5 mm/min.

During compression, load-deformation curves were recorded simultaneously. The maximum compressive strength was recorded in Newtons (N). The maximum compressive stress \( \sigma_{\text{max}} \) was expressed in MPa (1 MPa = 100 N/cm\(^2\)). The \( \sigma_{\text{max}} \) value for the iliac crest represents the average value between two tested specimens from the left and two from the right iliac crest, and the \( \sigma_{\text{max}} \) for the vertebral is the average value between two specimens from each of the vertebral bodies, T1, L1, and L3. For trabecular bone the intrabone variation was 20–25% for horizontal iliac crest bone specimens and 23–29% for vertical vertebral specimens. The intrabone variation between horizontal iliac crest and vertical vertebral body trabecular bone was 17–27%, resulting in a minimal true interbone variation (Mosekilde et al., 1985). The interindividual variation among individuals aged 20–80 years was 60–80%. For total vertebral bodies the interbone variation (variation between vertebral bodies in the same individual) was 11–14%.

Results

The maximum compressive stress \( \sigma_{\text{max}} \) of whole vertebral bodies showed a marked decrease with age from around 6.0 MPa at age 20 years to 2.6 MPa at age 80 (Fig. 1A). A similar decrease in \( \sigma_{\text{max}} \) from 4.4 MPa to 1.1 Mpa was observed for vertebral body trabecular bone (Fig. 1B). The regression lines describing the age-related decrease in total vertebral body and vertical vertebral trabecular bone \( \sigma_{\text{max}} \) respectively, were almost parallel. No significant difference was found between their slopes (\( -0.057 \pm 0.006 \) MPa/year vs \( -0.054 \pm 0.006 \) MPa/year (\( \bar{x} \pm SE \)), but their intercepts were different (7.07 ± 0.39 MPa vs 5.44 ± 0.37 MPa, \( \bar{x} \pm SE \) P < 0.01). At any age the compressive stress (expressed per cm\(^2\)) for whole vertebral bodies was about 1.6 MPa higher than for the trabecular bone.

The average cross-sectional area of the vertebral bodies increased with age (Fig. 2). The relative increase in area from age 20 years to 80 was about 25–30% in all the measured vertebrae (T5, T9, L2). Because of this increase in vertebral body area with age, the age-related decrease in total vertebral body compressive strength from the age of 20 to 80 years was reduced to 25–30% from the expected 57% (based on strength measurements per cm\(^2\)) to 46% (based on strength measurements per total vertebral body).

The anisotropic properties of trabecular bone in the center of the vertebral bodies, expressed as the ratio between the vertical and horizontal compressive strength (anisotropy index) showed a significant increase with age (\( y = 0.021x + 1.507, r = 0.49, P < 0.05 \)). From age 20 to 80 years the anisotropy index increased on average by 63%.

The average \( \sigma_{\text{max}} \) of the total vertebral bodies (T1, T2, L3) showed a highly significant correlation with the average \( \sigma_{\text{max}} \) of trabecular bone from the center of the vertebral body (T1, T2, L3, vertical direction) (Fig. 3). The slope of the regression line [0.90 ± 0.08 (\( \bar{x} \pm SE \))] did not differ significantly from 1, but the intercept (1.75 ± 0.21 MPa (\( \bar{x} \pm SE \)) was significantly positive (\( P < 0.01 \)). Furthermore, trabecular bone in the vertebral bodies (vertical direction) and in the iliac crests (horizontal direction) showed almost identical age-related decreases in \( \sigma_{\text{max}} \) (Figs. 1B, C). No significant differences were found between the slopes or the intercepts of the two regression lines. Finally, the average \( \sigma_{\text{max}} \) of the whole vertebral bodies showed a highly significant positive correlation with the horizontal iliac crest trabecular bone \( \sigma_{\text{max}} \) (Fig. 4). The vertebral body compressive strength (range 1.5–7.8 MPa) could be estimated from the mechanical tests on horizontal iliac crest trabecular bone, with an error of 0.92 MPa.

Discussion

The present study has demonstrated that both the internal and external architecture of the vertebral bodies changes with aging. The change in the internal architecture consists of an enhanced anisotropy of the load-bearing trabecular bone, whereas the change in external form is caused by a continuous periosteal growth. Both these changes will mitigate the effect on bone strength of the age-related decrease in bone mass with age.

Formation of bone is stimulated by the stresses or strains to which it is subjected (Minaire et al., 1974; Lanyon, 1981, 1994; Smith, 1994), just as these factors are important determinants in the modeling and remodeling processes.
A close feedback mechanism exists between physical activity and bone formation or adaptation. Thus, critical forces acting on bone in a certain direction result in such formation and adaptation of the existing bone that subsequent forces in the same loading direction are reduced (Frost, 1983). Hence, dynamic loading through daily physical activity not only stimulates bone formation and increases bone mass but also governs bone architecture and the changes in this throughout life. The forces normally acting on the vertebral bodies are vertical compressive forces (Pesch et al., 1980). When the trabecular bone mass decreases with age, often accompanied by a rarefaction of the trabecular structures (Parfitt, 1984), the compressive forces on the remaining trabecular structures will increase. To reduce this critical increase new bone is formed on the vertical trabeculae. The horizontal trabeculae, which are often disconnected or have disappeared, are not involved in this adaption of trabecular bone (Atkinson, 1967; Saville, 1967; Parfitt et al., 1983). The described alterations will result in an enhanced anisotropy of the trabecular bone in the vertebral bodies. This is in contrast to the age-related changes in the nonloadbearing iliac crest trabecular bone (Mosekilde et al., 1985). In the present investigation the failure stress for the horizontal trabeculae, which decreased at a greater rate than the vertical in the vertebral bodies, might be a consequence of perforation and disconnection of the thin horizontal trabeculae. In the iliac crest the trabecular network is more isotropic and homogeneous, with trabeculae of almost equal thickness and a more equal thinning with age.

In the present study we found a 4-5 mm increase in vertebral body diameter from age 20 years to 80 years. This caused an increase in the cross-sectional area of 25-30% in the same time interval and, therefore, a reduction from 57% to 46% in the age-related decrease in vertebral body CT max. Identical increases in bone width have been described in other sites of the skeleton, for example, the metacarpal bones or the skull (Garn et al., 1967; Adams et al., 1970), which are not subjected to major forces. The age-related increase in skeletal size may, therefore, be a generalized
Fig. 2. Age-related increases in vertebral body cross-sectional area of T₁ (A), T₉(B), and L₁ (C) in normal individuals.

Fig. 3. Correlation between whole vertebral body compressive stress (σₚₚ) and vertical vertebral trabecular bone σₚ in normal individuals.

Fig. 4. Estimation of whole vertebral body compressive stress (σₚₚ) from mechanical tests on horizontal iliac crest trabecular bone specimens in normal individuals. SEE, standard error of estimation.
phenomenon (Garn et al., 1967; Parfitt, 1984) not neces-
ecessarily coupled with stress or strain. On the other hand, some
studies (Frost, 1983; Smith et al., 1984; White et al., 1984)
have reported a close relationship between physical activity
and increasing width of the vertebral bodies. It has further
been proposed that the skeletons of osteoporotic women are
characterized by small vertebral bodies, which lack the ability
to increase in width with increasing age (Kreiner, 1982).

The vertebral bodies can be described as cylinders with
walls of thin cortical bone filled with an anisotropic network
of trabecular bone separated by bone marrow (Radin,
1991). Cortical and trabecular bone are two different com-
partments, changing in different ways with age (Riggs et al.,
1981; Wahner et al., 1983; Meier et al., 1984). In the present
study a highly significant positive correlation was found be-
tween the compressive \( \sigma_{\text{max}} \) of whole vertebral bodies and the
vertical vertebral trabecular bone, with a regression line
slope close to 1 and an intercept of 1.7 MPa. Furthermore,
at any age, the \( \sigma_{\text{max}} \) of the vertebral bodies was about 1.6
MPa higher than that of vertical vertebral trabecular bone.

Hence, the age-related decreasing strength of trabecular
bone is responsible for the decreasing strength of whole
vertebral bodies (Chalmers and Weaver, 1966; Bartley et
al., 1966). The cortical ring causes at any age an absolute
loadbearing effect of about 1.6 MPa. The relative load-
bearing effect of the cortical ring, however, increases with
age as the trabecular bone strength decreases. This finding
is in accordance with Rockoff et al. (1969), who, in a study
of 32 individuals, found that the cortical vertebral shell
contributed the same loadbearing effect for individuals aged
<40 years as individuals aged >40 years. However, the
differences in loss of strength between the two age groups
due to a removal of the central trabecular core were highly
significant.

In a previous study Mosekilde et al. (1985) found that
the vertical \( \sigma_{\text{max}} \) of vertebral trabecular bone correlated with
the horizontal \( \sigma_{\text{max}} \) of iliac crest trabecular bone. The strength of the vertical vertebral trabecular bone could be
estimated from mechanical tests on iliac crest trabecular
bone with an SEE of 0.90 MPa. This covariation in com-
pressive strength between loadbearing and nonloadbearing
trabecular bone is explained mainly by the observed parallel
age-related decrease in both variables.

The present study demonstrates a similar close relation-
ship between the strength of whole vertebral bodies and the
strength of iliac trabecular bone. The average \( \sigma_{\text{max}} \) of the
vertebral bodies could, over a range of 1.5-7.8 MPa, be
estimated with an error of only 0.02 MPa. This estimate is
possible because of the close relation between the \( \sigma_{\text{max}} \)
of whole vertebral bodies and that of central trabecular bone
together with the previously observed close relationship
between the \( \sigma_{\text{max}} \) of horizontal iliac crest and vertical vertebral
trabecular bone.

The present experimental circumstances do not reflect
normal biology in all aspects. The strength of whole vertebral
bodies was measured after exact planarparallel surfaces
were obtained by sawing 2 mm below the end-plates. The
compression did not lead to macroscopic changes in the
shape of the compressed bone. Furthermore, the applied
continuous compressive load was equally distributed over
the surface area. In normal life the compressive load is
repetitive, varying in intensity, localization, and direction
and influenced by the often irregular end-plates and the elasticity
of the intervertebral discs. In symptomatic osteoporosis the
fractures often involve the central trabecular bone without
affecting the surrounding cortical ring, resulting in depressed
end-plates or a biconcave vertebra. In other situations the
compressive load is largest on the anterior part of the verte-
bral body due to spinal bending. The resulting fracture will
create a wedge-shaped vertebral body with an intact pos-
terior part. In its most pronounced form the osteoporotic
fracture leads to a complete collapse of the vertebral body.
Because of the noted differences between the experimental
design and the natural course of osteoporotic fractures, it
is uncertain to what extent the applied results can be ex-
trapolated to in vivo situations. Furthermore, the observed
relationships were found in normal individuals. The relation-
ship between horizontal iliac crest and vertical vertebral tra-
becular bone compressive strength and the relative contribu-
tion of trabecular and cortical bone to the total vertebral
body compressive strength may be different in osteoporotic
individuals. The efficacy of predicting vertebral compressive
strength and fracture risk in osteoporotic patients from me-
chanical tests on iliac crest trabecular bone, therefore, has
to be assessed.

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