Acta orthop. scand. 47, 489–495, 1976

MECHANICAL PROPERTIES AND DENSITY OF BONE IN A CASE OF SEVERE ENDEMIC FLUOROSIS*

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Mechanical properties of 25 standardized specimens of compact bone from a 45-year-old man with extreme endemic fluorosis were compared with similar specimens of nonfluorotic bone. Data from dry and wet tested specimens were compared. Tensile strength, strain, energy absorbed to failure, and modulus of elasticity were reduced in fluorotic specimens while compressive strength, strain and energy were increased in both wet and dry specimens. Compressive properties exceeded tensile properties. Drying increased tensile and compressive strength and modulus but decreased tensile and compressive strength and energy absorbed. Dry specimens tended to follow Hooke's Law but wet specimens exhibited visco-elastic behavior. Wet fluorotic specimens had lower tensile properties but higher compressive properties and were more dense than fresh human compact bone.

Key words: human bone; mechanical properties; fluorosis

Accepted 25.v.76

Although there is an abundant literature on the biological effects of fluoride—more than 16,000 publications in 35 years according to Faccini (1969)—little research has been done on its effects on the mechanical properties of bone. The breaking strength of fluorotic bone in sheep was studied by Bell & Weir (1949); in dogs by Toshima & Tawara (1955) and by Henrikson et al. (1970); in rats by Naylor & Wilson (1967), Saville (1967), Beary (1969), Rich & Feist (1970), Nordenberg et al. (1971), and Wolinsky et al. (1972); in rabbits by Faccini (1969); and in Japanese quail by Chan et al. (1973).

However, a search of the available literature produced no references dealing with the effects of fluoride on the mechanical properties of human bone. This is surprising in view of the widespread use of fluoride in the treatment and prevention of dental caries. We were, therefore, pleased when an opportunity was presented to study the mechanical properties of human compact bone from a man with severe endemic fluorosis.

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* This research was supported in part by research grant AM03865, National Institutes of Health, United States Public Health Service.

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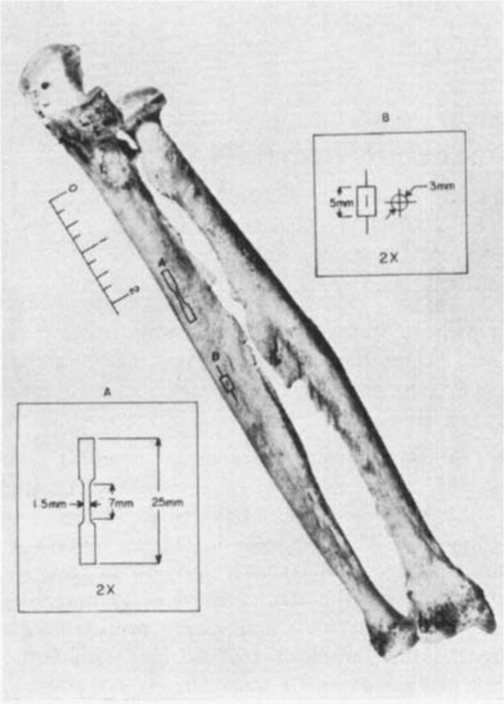

Figure 1. Left ulnar and radius from a 45-year-old man with extreme endemic fluorosis, showing shape and dimensions of test specimens.

MATERIALS AND METHODS

Material used in the present study consisted of fluorotic and nonfluorotic left ulnas and radii of middle-aged men.

The fluorotic bones from a 45-year-old Punjabi man were sent to us by Charles Nagant, M.D., Department of Medicine, St. Pierre Hospital, Catholic University, Leuven, Belgium, so that we could determine their mechanical properties. The nonfluorotic bones came from the osteological collection of the Department of Anatomy, The University of Michigan Medical School.

The Punjabi man had been almost completely bedridden for the 5 years preceding his death, from primary urinary infection and secondary infection of extensive bed sores. He also had a severe endemic fluorosis accompanied by extensive skeletal changes which have been described by Singh et al. (1962). The water in his native village had 0.95 mg per cent or 9.5 ppm of fluorine. Considering that he lived to be 45 years of age and probably spent most of his life in the same village, the amount of fluorine he had consumed must have been enormous. The mid-shaft of the radius had what appeared to be a healed fracture which was probably responsible for the large exostosis in the interosseous membrane (Figure 1).

Tensile and compressive test specimens of compact bone (Figure 1) from the fluorotic and the nonfluorotic bones were machined to a standardized size and shape with a No. 1000 Unimat equipped with a No. 1210 milling table. Only a few minutes were required to machine a test specimen and care was taken to prevent overheating and drying of the specimen during the process. Twenty-five specimens from the fluorotic bones and a comparable number from the nonfluorotic bones were tested.

Ultimate tensile and compressive strength of the specimens were determined by loading them to failure at a constant rate of 1.27 mm/min in a floor model Instron testing machine equipped with a 22.68 kg load cell. The specimens were tested under pure tension or compression in the direction of their long axis which was parallel with that of the intact bone. Specially designed wedge-shaped grips with Eastman 910 cement on the tabs were used to hold the specimens during a tensile test.

When mounting a specimen in the testing machine great care was taken to ensure that the specimen was perfectly aligned with the direction of the force so that during a test the force was uniformly distributed over the critical cross-sectional area of the specimen. In the tensile specimens the critical cross-sectional area was the reduced region but in the compression cubic specimens the cross-sectional area was the same throughout the specimen.

Tensile strain (percent deformation) occurring in a specimen during a test was measured with Budd Metafilm foil gages bonded directly to the specimen with Eastman 910 cement. Type C12-LXL-M 504 3 m/m gages with a resistance of 120 ohms and a gage factor of 2.01 were used. Compressive strain (percent deformation) was determined from differential movement of the specimen end surfaces and the cross heads of the testing machine.

From the stress and strain data obtained in a test, stress-strain curves were drawn from which the tangent modulus of elasticity, a measure of the stiffness of a material, and the energy the specimen absorbed to failure were computed. The modulus of elasticity, or ratio between unit stress and unit strain, was calculated from a tangent drawn to the straightest part of the stress-strain curve. The energy absorbed to failure was determined by measuring the area below a stress-strain curve with a compensating polar planimeter.

The effects of drying on the mechanical properties of the specimens was evaluated by testing some of them in the dry condition and others in the wet condition after they had been stored for several hours in Ringer's physiological saline solution. Among the fluorotic specimens, six were tested dry in tension and seven in compression, while among the wet specimens, five were tested in tension and seven in compression. Similar tests were performed on a comparable number of wet and dry specimens from nonfluorotic bones.

Mechanical property values obtained from the wet fluorotic specimens are probably more truly representative of those in the living subject than the values for the dry-tested specimens. However, data obtained from dry specimens are more useful for comparative purposes because both the fluorotic and the nonfluorotic specimens were obtained from bones that had been dry for several years. Comparable fresh material was unavailable.

Because of the long period (5 years) during which the Indian man was bedridden and the known effects of immobilization on the density and mechanical properties of bone (Kazarian & von Gierke 1969, Eichler 1970, Krasnykh 1969), the density of the fluorotic and the nonfluorotic specimens was determined by weighing them in air and in Ringer's physiological saline solution. Cubic compression specimens were used for the density determinations because it was easier to compute their volume than that of the irregularly shaped tensile specimens.

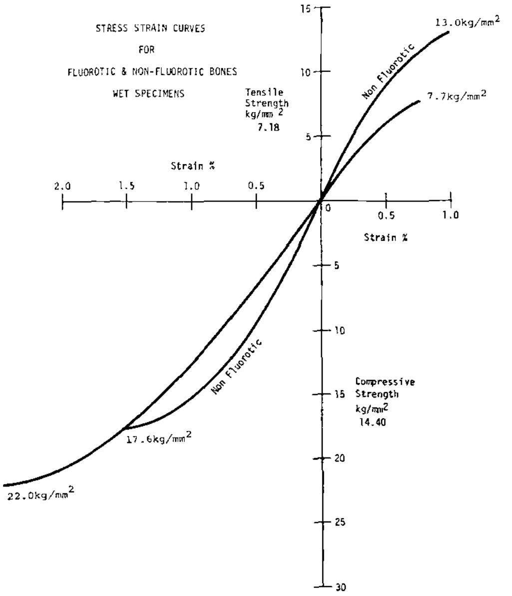

Figure 2. Average stress-strain curves for five fluorotic and nonfluorotic wet specimens tested in tension and seven tested in compression.

RESULTS

Mechanical Properties

From comparison of the stress-strain curves for wet tested fluorotic and nonfluorotic specimens (Figure 2) it is seen that the fluorotic specimens had a lower tensile strength and strain but a higher compressive strength and strain than the nonfluorotic ones. The fluorotic specimens also absorbed less energy to failure in tension (3.53 kg-cm/cm^3) than the nonfluorotic specimens (8.10 kg-cm/cm^3). However, in compression, more energy to failure was absorbed by the fluorotic (34.33 kg-cm/cm^3) than by the nonfluorotic specimens (17.59 kg-cm/cm^3).

Fluorotic specimens also had a lower modulus of elasticity (1,362 kg/mm^2) than the nonfluorotic specimens (2,178 kg/mm^2). This was indicated by the lower slope (53°) of the curve for the fluorotic specimens as compared with the slope (65°) of the nonfluorotic ones. In each case the degree of the slope represents the angle between the straightest part of the stress-strain curve and the strain axis.

When the stress-strain curves for dry tested fluorotic and nonfluorotic specimens are compared (Figure 3) it is seen again that the fluorotic specimens had a lower tensile strength and strain but a greater compressive strength and strain than the nonfluorotic ones. Energy absorbed to failure in tension was also less in the fluorotic (2.83 kg-cm/cm^3) than in the nonfluorotic specimens (5.03 kg-cm/cm^3). In compression, however, the situation is reversed, the fluorotic specimens absorbing 37.16 kg-cm/cm^3 to failure compared to an absorption of only 8.64 kg-cm/cm^3 for the nonfluorotic specimens.

Again the slope of the curve for the fluorotic specimens was lower (65°) than that for the nonfluorotic (69°),

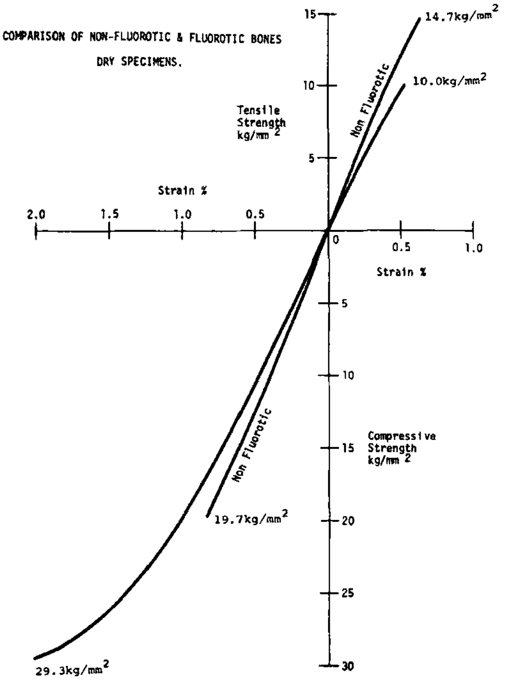

Figure 3. Average stress-strain curves for six fluorotic and nonfluorotic dry specimens tested in tension and seven tested in compression.

indicating that the latter had a higher modulus of elasticity. Actual modulus values were 2,133 kg/mm^2 for the fluorotic and 2,666 kg/mm^2 for the nonfluorotic specimens.

Effects of drying on the tensile and compressive properties of the fluorotic and the nonfluorotic specimens were also investigated.

Comparison of the stress-strain curves for wet tested and dry tested fluorotic and nonfluorotic specimens (Figures 2 and 3) shows that the ultimate tensile and the ultimate compressive strength as well as the modulus of elasticity of both types of specimens were increased by drying. The average modulus was 1,362 kg/mm^2 for the wet and 2,133 kg/mm^2 for the dry fluorotic specimens and 2,178 kg/mm^2 for the wet and 2,666 kg/mm^2 for the dry nonfluorotic specimens.

However, drying decreased the magnitude of the tensile and compressive strain in both fluorotic and nonfluorotic specimens. Thus, the average tensile strain was approximately 0.75 per cent for the wet and 0.55 per cent for the dry fluorotic specimens compared to an average compressive strain of 3.0 per cent for the wet and 2 per cent for the dry ones. Comparable values for nonfluorotic specimens are 0.95 per cent for the wet and 0.75 per cent for the dry specimens in tension compared to 1.52 per cent for the wet and 0.8 per cent for the dry ones in compression.

Energy absorbed to failure by the wet and the dry tensile tested fluorotic and nonfluorotic specimens was decreased by drying. Wet fluorotic specimens absorbed an average of 3.53 kg-cm/cm^3 of energy while similar dry specimens absorbed only 2.83 kg-cm/cm^3. When tested in compression wet fluorotic specimens absorbed 34.33 kg-cm/cm^3 and dry ones 37.16 kg-cm/cm^3 of energy to failure. The difference was due to the increased compressive strength of the dry specimens.

Dry nonfluorotic specimens tested in tension absorbed 5.03 kg-cm/cm^3 of energy to failure compared to an absorption of 8.10 kg-cm/cm^3 of energy by the wet specimens. When tested in compression the dry nonfluorotic specimens absorbed 8.64 kg-cm/cm^3 of energy to failure while the wet ones absorbed 17.59 kg-cm/cm^3 of energy.

The stress-strain curves (Figures 2 and 3) also revealed that in both wet and dry tested fluorotic and nonfluorotic specimens ultimate strength, strain, and energy absorbed to failure were considerably greater in compression than in tension.

The stress-strain curve for the dry nonfluorotic specimens was essentially a straight line to failure in both tension and compression indicating a marked tendency to follow Hooke's Law. Dry fluorotic specimens also had a straight line to failure in tension but in compression the curve deviated from a straight line. Stress-strains for wet fluorotic and nonfluorotic specimens were sigmoidal in shape showing that wet bone has a visco-elastic behavior.

Density

The average density of the fluorotic specimens was 2.01 g/cm^3 for the dry ones and 2.26 g/cm^3 for the wet ones in physiological saline. Similar dry specimens of *nonfluorotic* bone had an average density of 1.84 g/cm^3. The density value for the dry specimens of both fluorotic and nonfluorotic bone is probably a more accurate value for density of osseous tissue than that of the wet specimens whose density is increased by moisture entrapped within the spaces of the bone.

DISCUSSION

In most cases, data on the effects of fluoride on bones of experimental animals are not directly comparable to ours for human bone because of species variations and differences in testing methods. According to Yamada (1970) and Evans (1973) there is considerable species variation in the mechanical properties of bone even when the specimens and testing methods are similar. Generally, in studies with experimental animals intact bones were tested in bending or in torsion. In both of these tests the bone is subjected to a combination of tension, compression, and shearing forces which is quite different from our tests in which only one type of force was acting on the specimen. (For further information on stress distribution in bending or in torsion consult Harris (1963) or almost any other textbook on strength of materials.)

In addition to fluoride, the effects of reduced stresses on mechanical properties of bone must be considered because our fluorotic material came from a man who was bedridden for most of the last 5 years of his life.

Semb (1966) reports no significant differences in breaking strength (bending), modulus, and energy absorption between control and immobilized bones from dogs. However, Eichler (1970) found that the breaking strength of guinea pig femur, after 6 weeks of immobilization, was only 38 per cent of its original value, i.e. there had been a 62 per cent loss compared with the control bones.

Kazarian & von Gierke (1969) reported that the ultimate compressive load (kg) and deformation (mm) of lumbar vertebral bodies were two to three times less in specimens from monkeys immobilized in full-body plaster-of-Paris casts for 60 days.

Apparently Nordenberg et al. (1971) are the only authors who have investigated the effect of fluoride combined with immobilization on mechanical properties of bone in experimental animals. They found that NA_2Po_3F decreased breaking (tensile) strain of standardized compact specimens from rat tibias but tensile strength and energy absorbing capacity were not significantly affected. Specimens from immobilized (osteoporotic) tibias also had no significant changes. Our data are not comparable because our specimens were not osteoporotic.

Comparison of our data with those given by Yamada (1970) revealed that ultimate tensile strength, tensile strain, energy absorbed to failure in tension, and modulus of elasticity of our wet fluorotic specimens were all less than those of fresh normal human bone. However, our fluorotic specimens had a greater ultimate compressive strength and compressive strain than fresh bone.

One of the known effects of the absence of stress on the skeleton is a decrease in bone density. According to

Kazarian & von Gierke (1969), this was seen in some astronauts after being in a "prolonged zero-G-environment." Thus, in the 8-day Gemini 5 voyage the calcaneus and the metacarpal bones of both the pilot and the command pilot were reported to have a 20–30 per cent decrease in their density. Prolonged hypodynamia alone or plaster cast immobilization can also cause disuse bone atrophy and decrease in density (Krasnykh 1969, Hancox 1972).

The density decrease found in the astronauts of the Gemini 5 flight differs from our fluorotic specimens in which the average density was 2.26 g/cm^3 for the wet and 2.01 g/cm^3 for the dry specimens. These values are higher than any recorded by Blanton & Biggs (1968) for human compact bone except for the highest value of 2.100 g/cm^3 and 2.00 g/cm^3 found by Robinson and by Johnson, respectively. The maximum density value for our fluorotic specimens was 2.29 g/cm^3 which, as far as we know, is considerably higher that that found for human bone by any other investigator. Our density values strongly suggest that extreme endemic fluorosis increased the bone density of our subject in spite of any density-decreasing effects of being bedridden for the last 5 years of his life.

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