Mineral and mechanics of bone fragility fractures

A review of fixation methods

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This review focus on the role of bone fragility in the treatment of fractures. Other sources are referred to concerning the etiology of bone fragility, notably factors such as age, sex, race, life habits, falling tendency, and diet (Cummings 1985). Noninvasive assessment of bone mineral is assigned increasing importance in the understanding of osteopenic fractures (Ross et al. 1990) and may become a clinical tool in fracture care.

Bone is called fragile when it breaks under less than a normal load. In this review, bone fragility and osteoporosis are used synonymously. Bone is fragile in a number of diseases such as rheumatoid arthritis, osteomalacia, osteogenesis imperfecta, and bone tumor (Hooyman et al. 1984, Uhthoff 1986). Even diseases with increased bone density, such as osteopetrosis and Paget's disease, are associated with pathologic fractures. In these diseases, the bone may be as brittle as chalk.

However, the major cause of fragility of bones in the elderly is the reduced bone mineral. Two types of involutional osteoporosis have been delineated (Riggs and Melton 1983). Postmenopausal osteoporosis is designated Type I, and senile osteoporosis, occurring in women and men alike, Type II. A combination of the two types affects drastically the fracture epidemiology in elderly women. In experimental conditions, bone with reduced mineral breaks under a smaller load than normal bone (Vose and Mack 1963, Dalén et al. 1976, Alho et al. 1985). In accordance with these observations, the risk of fractures is increased in osteoporosis related to reduced bone mass (Ross et al. 1990).

The problem of senescence is multifactorial. The skin, ligaments and ocular lens all change with age, and it is hard to explain the 5-fold increase in Colles' fractures during the 6th decade by loss of mineral only (Alffram and Bauer 1962). Burstein et al. (1976) suggested that changes in bone matrix affect the fracture risk. Pogrund et al. (1986) found a correlation between osteoporosis and psoas muscle width, again suggesting that factors other than bone mineral also play a role in the increased fracture-susceptibility in old age. Lauritzen and Lund (1990) suggested padding of the hips to prevent hip fractures in elderly women with reduced subcutaneous tissue. Cummings (1985) found several factors other than osteoporosis that explain the increased hip fracture rate in the elderly.

The treatment problem in an osteoporosis fracture is twofold. Bone fragility reduces the possibilities of secure fixation and the old patient may be debilitated, which increases the risks of operation. Therefore, osteoporotic fractures in the elderly are often treated by closed methods. However, the demand for rapid restitution of function may be as urgent in an elderly as in a young patient.

Few studies relate the results of internal fixation to bone fragility, which is not systematically considered in planning the treatment of an obviously osteoporotic fracture. Large manuals and textbooks on fractures pass by osteoporosis unsystematically and with short comments. Lane et al. (1990) summarized the treatment of the three common fragility fractures of the hip, spine and distal radius. In the following, the basic morphologic and mechanical facts of bone fragility are reviewed, and the importance of bone fragility for internal fixation of fractures is outlined.

Morphology and biochemistry of bone fragility

Radiographic osteopenia results from either decreased mineral content of bone matrix or reduction of the absolute amount of bone tissue (Adler 1983). The former is typical for osteomalacia, where part of the existing osteoid is not mineralized. In osteoporosis, the amount of matrix is reduced, which limits the amount of mineral. In old age, osteoporosis and osteomalacia may be combined (Aaron et al. 1974, Hoikka et al. 1982) resulting in a greater reduction of bone mineral than in either of the diseases alone.

In osteoporosis, the bone trabeculae are thinned, even abrupted, which increases the porosity. Interestingly, the total effect seems to be a nearly linear relationship between reduced bone strength and mass (Hayes 1991, Alho et al. 1992). Techniques for characterizing bone mineral microstructure suggest that the hydroxyapatite crystals in osteoporotic bone are larger and more perfect than in age-matched controls (Boskey et al. 1990). In addition to bone mineral, bone-matrix collagen may have importance for the mechanical properties of bone, as the studies by Burstein et al. (1976) suggest.

Assessment of bone mineral related to fractures

Histomorphometry, which is useful in the diagnosis and treatment of metabolic bone diseases, is impracticable in the assessment of fracture risks in large patient populations. Osteoporosis being the prevailing cause of bone fragility, decreased bone mineral values in densitometric assessment are often designated osteoporotic, although such studies only can show osteopenia.

Bone mineral, bone mineral density, and bone mineral content are terms which are often used too loosely. To understand the problems of osteoporotic bone, exact definitions are necessary. In simple physical terms, bone density depends essentially on the calcium concentration per bone volume ($g \times cm^{-3}$) and may only be expressed by a calcium-related parameter determined in a volume unit. Further, the mass of bone is essentially given by mass = calcium concentration × volume ($gcm^{-3} \times cm^{3}$).

It is important to understand the principal differences between various densitometric methods. Photon and x-ray absorptiometry, which is very useful in epidemiologic and clinical bone mineral research, does not express real bone density, but generates a partly integrated measure ($g \times cm^{-2}$). On the other hand, the fully integrated measure, bone mineral content, determined by these methods is related to the real bone mass (Wahner 1989). The limitation of these absorptiometric methods makes them less suitable for biomechanics-related studies.

Despite the sources of error, such as marrow fat, beam hardening, scatter, and partial volume effect, quantitative computed tomography (QCT) is a clinically useful analytic method (Høiseth et al. 1991). The bone density-related measure (CT unit) determined by single energy QCT is related to calcium concentration ($g \times cm^{-3}$), and the bone mass-related measure (CT unit x volume) to total calcium content (g) (Benterud et al. 1991). As mentioned above, the handicap in elderly women does not appear to be a reduced bone density only but, even more importantly, a smaller bone volume than in men (Alho et al. 1988).

Mechanics of fragile bone

Several studies have shown that the strength of bone is related to its mineral content (Hayes 1991). Reduced bone mineral in osteoporosis reduces the holding power of implants (Wittenberg et al. 1991).

Bones are elastic and they adapt to the loads of daily life by recoiling. If the load exceeds the yielding point, permanent deformation and fracture occur. Like any elastic material, bone tissue has a fatigue limit. Repeated bending loading above this limit results in fatigue fracture. The elasticity of bone is viscoelasticity. Therefore, the resistance of bone and the type of fracture are related to the velocity of force. However, this property is of little importance for the occurrence of low energy fractures, typical for the elderly.

The mechanical strength of bone as a material is correlated with its density (Hayes et al. 1991), especially for cancellous bone (Alho et al. 1992). The correlations to cortical bone strength seem to be less good (Snyder and Schneider 1991). The strength of the femoral neck is correlated to bone mineral assessed by various absorptiometric methods (Vose and Mack 1963, Dalén et al. 1976, Alho et al. 1985, Esses et al. 1989, Husby et al. 1989, Beck et al. 1990). Although linear equations have explained the association between bone mineral and mechanical strength in many human bone materials, the studies of Currey (1969) on animal bones suggest that an increase of bone density above an optimal level reduces bone strength. This may explain the brittleness of sclerotic bone.

With increasing age, the material properties of bone change; Burstein and coworkers (1976) observed that cortical bone absorbs less energy before fracture and is less elastic - the ultimate strength is reduced more than the elastic modulus. Simultaneously, the stiffness in the plastic zone of deformation is increased, which the authors suggested is a reflection of the aging of collagen. However, reduced bone mineral is the main cause of susceptibility to fracture in the elderly (Ross et al. 1990, Hayes et al. 1991).

The structural strength of a whole bone is determined by the properties of its material and by the distribution of the material—the bone geometry (Hayes 1991). Also, the weakness of bone in women does not seem to be caused by a higher degree of osteoporosis only but just as much by a smaller bone size than in men (Alho et al. 1988).

The Wolffian (1892) teleology also acts in the involutional osteoporosis changing diaphyseal bone geometry. Simultaneously with an endosteal bone resorption, the outer bone diameter increases (Smith and Walker 1964). Thus, although the cortical area is reduced, the area moment of inertia is retained to some extent, resulting in a relatively smaller reduction of strength. This phenomenon seems to occur in the femoral neck as well, but to a lesser extent in women than in men (Beck et al. 1992).

In age-related osteoporosis, both cortical and cancellous bone mineral are reduced. The reduction concerns both the bone matrix and the mineral of the matrix. The reduction does not occur equally in axial and appendicular skeleton. This dissociates osteoporotic fractures of the spine, distal radius, and hip (Bohr and Schaadt 1983, Mazess et al. 1988), and explains an individual proneness to these three types of fracture.

Few studies address the problem of impaired implant fixation in osteoporotic bone. In an autopsy study of transpedicular screws, laminar hooks, and transpedicular wires, Coe et al. (1990) found that the hooks were superior in a bone with decreased mineral density. Cameron et al. (1975) could enhance the pull-out force of screws in osteoporotic bone by polymethylmethacrylate-cement reinforcement. Soshi et al. (1991) observed a relationship between the severity of osteoporosis and the fixation strength of pedicle screws. Bone cement doubled the pull-out force. In low-grade osteoporosis, increased screw-size improved the pull-out force, but not in high-grade osteoporosis.

Internal fixation of fractures related to osteoporosis

It seems that osteoporotic fractures are more comminuted than fractures of normal bone. Using outer and inner cortical diameter as measures of osteoporosis, Elabdien and coworkers (1985) showed that 3- and 4-fragment trochanteric fractures were more numerous in patients with the poorest bone stock. Allfram and Bauer (1962) found a relationship between increased incidence of displaced fracture and old age. On the other hand, fracture comminution was unrelated to the patients' age in a study of femoral neck fractures where the comminution was related to the result of internal fixation (Alho et al. 1992b). In the lateral tibial condyle, the width and length of fragments were reduced and related to osteoporosis, as estimated by a Singh-type radiographic osteopenia index (Foltin 1988).

Systematic, clinical studies of the effects of osteoporosis on internal fixation are few, and special strategies to treat fragile fractures are seldom applied in preoperative planning. It is well understood that fractures of the hip have to be treated operatively due to the obvious adverse effects of conservative treatment on morbidity and mortality. The same active policy is advantageous in the treatment of femoral shaft fractures (Moran et al. 1990). Extreme bone fragility is often experienced as an unexpected, disastrous situation intraoperatively; screws do not hold, the bone is splintered during reduction and fixation attempts. Special solutions have been suggested for such situations. Screws may be fixed with nuts. Cerclage wiring may hold where screws lose their grip. In extreme situations, polymethylmethacrylate cement has been suggested (Sarmiento 1973, Harrington 1975, Bartucci et al. 1985). Although not proven in any comparative clinical study, it seems that fractures of the distal end of the femoral shaft in the elderly may do better after an intramedullary nailing than after an angled blade-plate osteosynthesis (Strømsøe et al. 1990, 1993). Kolmert et al. (1983) suggested that semi-elastic fixation with two intramedullary rods prevents the failures observed with the use of rigid internal fixation in osteoporotic bone.

Of the three most common types of osteoporosis fractures, fractures of the hip, distal end of the radius, and the spine, the first two are as a rule treated operatively. However, special strategies where osteoporosis is taken into consideration are used to a very limited extent. Fractures of the distal end of the radius are seldom treated operatively in the elderly, and treatment of low energy fractures of the spine is exclusively closed. Right or wrong, the choice of operative treatment is generally made on the basis of the fracture type and location and not the quality of bone.

Fractures of the hip

High age increases the failure rate (Alho et al. 1992b). In experimental autopsy studies, weak associations were found between bone mineral and the resistance to a load of implant/bone constructs (Husby et al. 1987, Swiontkowski et al. 1987).

There seems to be a relationship between trochanteric fracture comminution and age of the patient (Elabdien et al. 1985), in contrast to cervical fractures (Alho et al. 1992).

Indirectly, this affects the treatment of the trochanteric fracture. Stable fractures may be treated by simpler means than comminuted ones. In comminuted fractures, intramedullary polymethylmethacrylate has been used for stabilization and the results seem favorable (Sarmiento 1973, Harrington 1975, Bartucci et al. 1985). The authors stress a strictly intramedullary location of cement to allow good periosteal healing. Intramedullary fixation devices in contrast to plates in the lateral cortex have theoretical, mechanical advantages in increasing the margin of fatigue safety (Cochran et al. 1980). Their clinical superiority remains, however, to be determined (Calvert 1992).

Fractures in rheumatoid arthritis

Femoral neck fractures are more frequent in patients with rheumatoid arthritis than in the general population (Hooyman et al. 1984), but the failure rates after internal fixation of displaced fractures are high. Therefore, endoprosthetic replacement has been recommended, even in relatively young patients (Strömqvist 1984, Strömqvist et al. 1988, Bogoch et al. 1991). The weakness of bone in rheumatoid arthritis may result from changes of bone mineral and matrix and be different from both osteoporosis and osteomalacia (Lieberman et al. 1988). Larsson and Elloy (1990) found a reduced holding power of implants in the rheumatoid femoral head. Unfortunately, they did not relate their results to bone mineral in order to test the hypothesis of Lieberman et al.

Fractures of the distal radius

Reduction of Colles' fracture in an elderly patient is often lost. McQueen et al. (1986) concluded that rereduction of a fracture gives poor results in patients over 60 years of age. Alternative methods, such as bone grafting, external fixation, and pinning, have been used. However, these methods have not been analyzed in a multifactorial setting where age or osteoporosis would be a factor. Schmalholz (1989) made a prospective comparison of two series of fairly old patients, where one series of redisplaced fractures was rereduced and immobilized in plaster and the other series was treated with filling of the dorsal defect with polymethylmethacrylate. The operated patients did better with regard to joint motion and strength of the hand. Differentiated treatment of the fractures of the distal radius is obviously required (Editorial, Acta Orthop Scand 1989).

Fractures of the spine

These fractures are often considered as a medical/endocrinologic problem. If operative treatment is chosen for selected, unstable fractures with neurologic involvement, the special nature of osteoporotic bone, which limits the choice of fixation methods, should be clearly understood. The hold of pedicular screws seems to be poorer than the hold of posterior instrumentations (Coe et al. 1990).

Conclusions

Increasing knowledge of fragile bone has been gained by noninvasive mineral assessments. Their future importance seems to be 2-fold. Firstly, it seems likely that patients with low bone mineral will be treated to try to increase their bone mineral or, at least, to keep it steady. Secondly, bone densitometry would help the care of selected fractures in the elderly where treatment might be chosen according to the strength of the bone stock.

Increased understanding has also been achieved by mechanical autopsy studies. However, compared to the extensive literature on biomechanics of osteopenic bone, relatively few studies address the mechanics of internal fixation in fragile bone, although it seems obvious that the retention of osteosynthesis in elderly bone is related to the bone mass. Direct clinical evidence is also scanty.

In many locations, osteoporotic fractures may need special solutions. It seems that osteosynthesis, with plates and screws which have their definite indications in younger patients, may be replaced by alternatives, such as cerclage wiring and intramedullary implants. Polymethylmethacrylate has been a good adjunct to strengthen screw fixation and to fill defects after compression of fragile cancellous bone. More studies are needed where the bone mineral is related to fractures.

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