PERSPECTIVE ON THE LONG BONES FROM THE POINT OF VIEW OF THEIR FUNCTIONAL STRUCTURE

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ABSTRACT (online version)

The bones are not inert structures. They are submitted to a permanent internal remodeling as an adaptation to the various mechanical strains. The influence of the external forces acting upon them is reflected within their functional structure, the bones harmonizing within the mechano-structures, in whose genesis the action of the mechanical factors stands out. The bones are organized in such a way so that a maximum of functional effect can be obtained with a minimum of material. This article presents structural characteristics of the long bones from the point of view of their organizing under the action of the mechanical forces.

KEY WORDS: long bones, functional structure, mechanical forces.

A complex perspective on the anatomic formations cannot be realized by simply describing them, but by associating this descriptive approach of the structures with the interpretation of their causality and by establishing some correlations between structure and function. The functional structure is the structure considered as a consequence of the function, taking into account the genetic component, as well. An important moment in the outlining of the notion of functional structure was that in which H. von Meyer presented the functional structure of the superior epiphysis of the femur, showing that the distribution of the bony trabeculae is done according to the pressure and traction lines.

The most obvious relations between the function fulfilled by an organ and its structures can be found at the level of the bones. Both external mechanical forces (of compression, bending, torsion, shearing, traction) and internal mechanical forces (resulting from processes of development, vascular pressure etc.) are acting upon bones. Any material, therefore the bone tissue as well, on which a stressing force acts, reacts with an equal and contrary reaction force. The action force acts in a couple with the reaction force, which has as a consequence the entering of the bone in a special condition, called the tension condition, the unitary efforts condition or the stress condition. The interior mechanical forces maintain the bone in a state of minimal tension (Baciu, 1981). These phenomena have consequences at the structural level, realizing a functional structuring in relation with the
mechanical strains, the structure of the bone being a mechano-structure. This can be realized so that a maximal resistance can be obtained with a minimum of material, this type of constructions being absolute minimal constructions. The arrangement of the bones is not accidental, but it is determined mostly by the mechanical strains they are submitted to, being in a permanent adaptation to these influences.

The long bones develop from hyaline cartilaginous models. They are submitted early to the mechanical strains by the muscular contraction and the tension state of the surrounding soft tissues. It is unlikely that the resultant of these forces coincides with the axis of the future bone; therefore this will be submitted to bending. The maximum point of bending will be approximately at the middle of the model and corresponding to it there will appear a hydrostatic point, in the sense of the elasticity theory. In accordance with the causal histogenesis theory advanced by F. Pauwells (cited by Benninghof, 1975), (according to which in the regions submitted to continuous hydrostatic pressure, there appears hypertrophy and then degeneration of the cartilaginous cells with the resorption of the surrounding matrix and the transformation of the hyaline cartilage in calcified cartilage, enchondral ossification taking place), the same thing happens in this hydrostatic point at the maximum level of bending, and there can be observed the appearance of the periosteal bony collar at the same time with the hypertrophy and degeneration of the cartilaginous cells. The ossification progresses towards the extremities of the bones. In the cartilaginous epiphyses there appear different tensions, which determine the appearance of one or more of these hydrostatic points representing the ossification epiphysis centres. The ossification centre grows up and develops both in the direction of the articular surface and in that of the bony diaphysis. The ossification progresses towards the articular surface until the layer of cartilaginous tissue that remains reaches the thickness where the strains that the articulation is submitted to determine an optimal deformation for the maintenance of the cartilaginous tissue. It is well known that the intermittent pressure that appears at the articular moves is essential for the maintaining of the articular cartilage. Its missing has as a result the replacement of the cartilaginous tissue with bone tissue. The functional strain has not only the role of maintaining the articular cartilage, but it also constitutes a stimulus for its proliferation. Thus, in the case of the articulations that are submitted to a stronger strain, this “optimum deformation of maintaining the
cartilage”, which is produced by articular charging, reaches more deeply than it does in the case of the less strained articulations. This is the reason why the articular cartilage is thicker in the first situation. On the other hand, the same cartilage, if in a state of prolonged rest, atrophies and can lead to ankylosis (Benninghof, 1975).

The hyaline cartilaginous tissue can persist only under certain conditions of mechanical strain and it has a low tolerance limit to any modifications of these conditions. The bone tissue is more adaptable to various strains, behaving as a technical regulator. The theory of the causal histogenesis does not presuppose a different kind of mechanical strain to explain the appearance of the bone tissue. According to it, the bone tissue differentiates where a pre-existing support tissue is mechanically strained, but without producing an exaggerated deformation. It is a secondary support tissue which can be formed from the conjunctive tissue or from the cartilaginous one, these being the departure points for the membranous ossification and for the enchondral ossification. The tissue that forms initially is the primary bone tissue, out of which, later, the secondary bone tissue, compact or spongy, is formed; this differentiation is directed by the mechanical strains, too.

As it is well known, the spongy bone tissue structures the epiphyses of the long bones. Its organization in trabeculae with various orientations constituted the subject of research that began a long time ago. After von Meyer’s presentation of the functional structure of the thighbone, the studies extended upon the other bones as well; a series of laws has been advanced, concerning the architecture of the epiphyses in relation with the action of the mechanical forces, especially in pathological conditions in which the articular bone segments had been maintained, for a long time, in inappropriate positions. However, these laws (Delpeche’s law, Wolf’s law, Roux’s law) did not manage to catch the complex aspects of the correlations between the mechanical forces and the functional architecture of the bone. According to them, the intensity of the mechanical factors is neglected, and any pressure would be followed by bone formation, while any absence of pressure would be followed by the resorption of the bone. In what concerns the pressure, it was later observed that it can have values favourable to bone formation or unfavourable. The favourable pressures are those which do not surpass the values that normally act upon the bones. They can be considered functional pressures and have values of 8-15 kg/cm2 bone (Baciu, 1981).
Through their action on the bones, the forces create tensions inside them. The propagation direction of the main tensions in the bone is considered a trajectory. Their materialization is realized through a three-dimensional net of arrangement of the trabeculae, which corresponds to the specific nature of the mechanical strains. Thus, the main trabecular systems of the superior epiphysis of the femur are: the lateral trabecular system, the medial trabecular system, the trabecular system of the great trochanter and the trabecular system which has the origin in the arch of Adams (Niculescu et al, 1995). Their orientation is mainly influenced by the action of the pression force produced by the weight of the body and by the action of the traction force produced by the abduction muscles (Fig. 1).

FIG. 1. Orientation of the trabecular systems in the superior epiphysis of the femur under the influence of mechanical forces (1 - trabecular system of the great trochanter, 2 - lateral trabecular system, 3 - medial trabecular system, 4 - trabecular system with the origin in the arch of Adams, A – pressure force, B – traction force)

K. Tittel (1970) compares the phenomenon of arranging the trabeculae according to trajectories with the arranging of iron filings in a magnetic field. The structure of the bone tissue organized according to the
main trajectories is a trajectorial structure. The trajectories can be evaluated mathematically and to a certain degree they have been observed with the help of the fotoelastic method or of the varnish covering method (Braus 1954). But, the relation between forces and the trabecular model is often more complex than a simplified mathematical analysis applied on bone sections or models (Kummer 1972, cited by Williams 1989). A fotoelastic technique which reveals stress patterns in bones and plastic models by polarized light was introduced by Hallerman (1934). Brekelmans (1972) emphasized its limitations. Benninghoff used the split-line technique. He punctured the bone with a round-bodied needle that produces a surface pattern of split-lines and cracks. He considered that this surface pattern follows distribution of osteons orientated in axes of compression or tension. Later, various authors (cited by Williams 1989) gave different interpretations to this phenomenon. Thus, Tappen (1954) claims that it is due to the immature osteons, Isotupa (1972) considers that it reflects the distribution of the points with a reduced resistance as a result of vascular spaces, and Buckland-Wright (1977) also attributes them to the weaker regions, but believes that this technique is not sure enough for the analyses of the transmission of forces and bone structure. Recently, computer simulation has been used for the analyses, on the spongy bone, of the morphological and structural consequences of the quantified mechanical strains (Jacobs, 2000).

The lamellae parallel the long axis of the trabeculae. Large trabeculae may contain Haversian systems of concentric lamellar bone (Sternberg, 1997). The most important trabeculae are in such a way arranged that their surface can be found in the plane of the forces, and not perpendicular on them. Thus, a maximum of resistance can be obtained with a minimum of material, the bones being absolute minimal constructions.

The spongy bone tissue from the short bones, for example those of the vertebrae, or from the epiphyses of long bones submitted only to pressure or, mostly, to its action (the inferior epiphysis of the radius, tibia, toes) is organized in the form of linear trabeculae oriented in the direction in which pressure acts; they are connected through little perpendicular slides which contribute to the support of the linear trabeculae. In the case of the bones submitted to a bending force as well (the thighbone), their spongy bone tissue is organized in trabeculae with a curved orientation, archformed, which cross one another in right angles (Braus 1954).
This spongy structure of a bone should not be analyzed isolated, restricted to a bone and independent of the bones that it is in contact with, because, just like the way in which the trajectories are transmitted from a bone to another, the main trabecular systems are continued in the next bone. In the same way in which a single bone represents only a part of the whole system of body support, the trabecular structure of a single bone can be considered only a part of a whole.

A decrease in the stability of the trabecular net of the spongy bone can be found in osteoporosis, situations in which various perforations of the trabeculae have been noted, perforations which lead to a diminuation of their competence from a mechanical point of view. The repairing mechanisms, such as the forming of micro-calluses, can cause errors when the density of the trabecular bone is measured (Delling, Hahn, Vogel, 1993).

The **compact bone tissue** in the interior of the diaphysis presents a functional structure as well, although it is not a trajectorial structure. It is formed of osteons with a longitudinal orientation, parallel with the bone axis. The diaphysis compact is submitted both to pressure force, which acts in the direction of the length of the bone, and to a bending force. The latter one appears because under the action of the muscular traction and of the corporeal weight there appears a slanting force compared with the bone axis. Therefore, the tensions that appear in the bone are not transmitted rectilinear and parallel, but they take the form of arcs that cross one another in a right angle. Braus (1954) demonstrates, with the help of a tubular model which represents the diaphysis and which is submitted to a bending force, that the trajectories that appear are archformed and are crossing in a right angle if they are observed from a perpendicular position on the plane of the bending force, while the same trajectories, if observed from the plane of the bending force, have, mainly, a longitudinal direction. When the plane in which the bending force acts is changed, the trajectories change accordingly.

The structure of the compact bone tissue is not a trajectorial structure, because it consists of osteons with a longitudinal orientation, but it is, at the same time, extremely favourable, because it always takes over the main tensions, irrespective of the plane the bending force acts from, while a trajectorial structure would only take over the main tensions in a certain plane.

If we refer to the osteons themselves, they are practically systems of tubes introduced one in another, representing an architectonic adaptation
which offers a bigger resistance to the bone. The same quantity of material
arranged in the form of a tube is more resistant than it would be if it were
arranged in the form of a compact column; the tube supports a bigger weight
than a compact column of the same diameter. The osteons are tightly bound
by intermediary bone lamellae, constituting a structure that has been
compared with breccia.

Every lamella of the osteon is formed out of collagen fibres, whose
essential mechanical characteristic is their resistance to traction. Different
hypotheses concerning the orientation of the fibres of the lamellae have
been advanced; the studies realized with the help of the electronic
microscope confirmed the existence of the fibrilar devices that have been
briefly described by Gebhardt. Thus, every lamella of an osteon contains
collagen fibres oriented in a spiral around the central channel and mostly
parallel. The fibres of two neighbouring lamellae will have different
directions, crossing one another under varying angles. This fibrilar
organization plays a part in the consolidation of the osteon structure, too.
The opposite orientation of the collagen fibres in two neighbouring lamellae
is a necessary condition for a good functioning of the bone tissue. If they
were wrapped up in the same direction, the pressure and the traction forces
acting would produce, beside the lengthening or the shortening of the
propeller’s pace, a rotation movement of the fibrilar system. The inclination
of the fibres in the juxtaposed lamellae occurs under various angles, and the
resistance to the different deformations that could be produced by a pressure
or traction force varies according to this inclination angle. As Gebhard
shows (cited by Rouviere, 1939), a spiraled system with a marked slope
reacts to a pressure that acts in a longitudinal direction by considerably
expanding its transversal diameter, while its vertical diameter is relatively
diminished. If, on the contrary, the spiraled system has a little slope, the
effect of the same pressure will be especially that of the diminution of the
vertical diameter, while the transversal diameter is a little increased. In the
situation in which the same pressure is applied to two neighbouring spiraled
systems, concentric and with the fibres having a little slope and,
respectively, a marked slope, every system will correct, in part, (just like in
the case of two neighbouring lamellae in the bone tissue) the main
deformation that pressure tends to produce in the neighbouring system. The
spiral arrangement of the fibres offers to the lamellae the capacity to damp
the shock that might appear in the case of a sudden application of great
pressures on the bone, in this way diminishing the risk of consecutive bone fractures. For the ensurance of the resistance of the bone tissue contributes both the arrangement modality of the lamellae within the osteons, and the arrangement of the collagen fibres in the structure of the lamellae, to which the collagen fibres themselves should be added, because they are characterized by increased resistance. Some recent research (Marotti, Muglia, Palumbo, 1994) show that the bone lamellae are not formed out of collagen fibres with a parallel arrangement (as the classical theories say), but are formed out of strongly intertwined fibres, and the lamellation appears as a result of the alternation of layers rich and, respectively, poor in collagen. A modification in the arrangement of the collagen fibres has been observed at the experiment animals (rats) in conditions of imponderability (Turner, Bell, Duvall, 1985). They discovered modifications at the level of the tibia diaphysis, where the collagen fibres had a preferential orientation parallel to the periosteal surface, and also the hypo-mineralization of the matrix. They also noticed the decrease in the resistance to torsion.

The medullar channel contributes, as well, to the realization of an increased resistance of the bones. Due to the fact that an empty column of a bigger diameter is stronger than a compact one of the same length, the presence of the medullar channel in the centre of the diaphysis makes the bones lighter and stronger. If it weren’t for this channel, the bones would be much heavier and this would lead to difficulties in the movement of the body.

A general perspective on the behaviour of the bone compared to the behaviour of any construction material at the action of external forces shows that the material deforms in a passive way (elastic or plastic deformation) or, in the case of extreme strain, it breaks, while the bone tissue reacts in a totally different manner. Pauwells (cited by Panait, Gh. et alii 1997) shows that the bone is in a fluctuating equilibrium, there taking place either an increase in the deposit of the bone tissue in the regions where the tension is stronger, or an increase in its resorption in the regions where the tension is smaller or where it surpasses certain limits. Everything relies on a feed-back mechanism, which ensures a differentiated adaptation, according to the functional strains.

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