Structures and Properties of Growing Bone

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Structure of Bone

Our intention is to give a summarized review of bone structure and relevant basic information about fracture biomechanics, especially in the child.

The most important data concerning these subjects are derived from clinical experiments during treatment of child fractures. In general, it is accepted that the anatomy, the physiology and the biomechanics of child bone are not the same as in adults. It is evident that these differences influence the way in which forces are acting on the body as well as their reactions. First of all we draw your attention to the bony structure. Comparing the child bone with the adult, differences are seen in the macroscopic and radiological view, involving the length, width, periosteum and prominences, especially referring to the presence of the epiphyses.

Without magnification the periosteum in the child bone is identified without difficulty. It is a thick, well-distinguished layer, which in some types of fractures can work like a hinge. Histologically it is composed of rows of plump osteoblasts lying between a thin outer fibrous sheet and the underlying bone. As growth ceases these rows of plump osteoblasts are replaced by layers of thick fibrous connective tissue. On some places primitive mesenchymal cells exist to provide more bone when needed. Stripping of the periosteum, as occurs when the continuity of bone is disrupted, leads to haemorrhage from the periosteal vessels and the Volkmann’s canals. Together with the nutrient arteries they form the sources of blood supply to the cortical diaphyseal bone.

Bone is a highly specialized form of connective tissue. We distinguish three types of connective tissue: (1) fibrous; (2) cartilage, and (3) bone. Each one has its own differentiated cells producing their characteristic
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All connective tissues contain two components: (1) the cells, derived from the primitive mesenchyme, and (2) the matrices. The most striking difference is that bone is a hard material. This hardness results from deposition of inorganic minerals within the soft organic matrix. The matrix of bone has a fibrillar structure, the fibres are mainly those of collagen. Mechanical properties such as compressibility, rigidity and elasticity are governed in part by the amounts and morphological arrangement of these fibres in the tissue. Between the fibrillar structure there exists the ground substance, also formed by the blast cells, forming together the non-mineralized osteoid.

Furthermore, we distinguish the cells of bone as follows:

(1) The bone formers or osteoblasts help to make bone and are seen wherever bone is being laid down, in sheets under periosteum, around trabeculae of cancellous bone. They are small, double staining cells, with a single nuclei and contain the enzyme phosphatase. They are involved in the formation of osteoid and its calcification. As bone grows they become incorporated into it as stable osteocytes.

(2) The bone destroyers, or osteoclasts, are large, multinucleated cells with phagocytic abilities, located around bone trabeculae and they remove bone as required for the remodelling process. Their action is probably controlled by the parathyroid hormone.

Bone is formed by the osteoblasts, which must be present before bone is made. These osteoblasts always have cytoplasmic arms that contact or connect with one another. During the time that the intercellular substance is being secreted these cytoplasmic arms serve as molds for tiny passageways, called canaliculi, providing communication between adjacent osteoblasts and the surface in which the bone is forming. When the osteoblasts are completely surrounded by the intercellular substance they have secreted, then they are termed osteocytes. The organic substance then becomes impregnated with calcium salts and so is rendered stone-like. The process described here is termed osteogenesis or ossification.

According to the structure of the collagen fibres we distinguish two types of bone:

(1) Lamellar, compact bone, characterized by new layers being added to bony surfaces in an orderly way. The fibrils are mechanically arranged and it has a relatively greater content of cement and minerals and fewer cells which are more regularly arranged. This type of bone contains Haversian systems, also called osteons: it is a compact bony structure consisting of a blood vessel in its canal providing nutrition to the osteocytes in the surrounding lamellae.
(2) Woven bone, composed of irregular trabeculae, is commonly very cellular. The intercellular substance is characterized by thick bundles of collagenic fibrils, irregularly arranged. This type of bone takes up less mineral than the lamellar bone, so it is not as strong as opaque to X-rays as lamellar cortical bone. This type of bone is seen in the growing child, the primary fracture callus and in the morbus Paget.

Another structure we may encounter in child bones is formed by the epiphysis, the centres of ossification responsible for forming bone in the ends. The cartilage cells, here centralized are maturing and become calcified and finally will die. At the end all the cartilage is replaced by bone, leaving articular cartilage at the surface. Between the diaphyseal and epiphyseal centre a disc or plate is left. In this disc two processes take place, namely (1) interstitial growth of cartilage cells which tends to thicken the plate, and (2) calcification, death and replacement of cartilage cells, which process tends to thin the plate.

In the child this disc is the site of tremendous cellular activity. The growth of bone occurs by increase in length and in diameter by (1) epiphyseal interstitial growth, (2) mechanism of apposition and (3) remodelling process: in length only by proliferation of cartilage cells at the epiphyses and their replacement by bone. Linear growth ceases when the epiphyses fuse with the shaft of the bone. This process is under control of hormones. Growth in diameter occurs by new layers of bone being added to the outside of the shaft, while at the same time, bone is dissolved away from the inside. New bone is laid down under the periosteum by the osteogenic layer of that membrane.

Throughout life, bone is undergoing a physiological turnover of both cancellous and compact bone. The formation and resorption processes normally must be in balance. In growing bone, bone formation far exceeds bone resorption.

In conclusion we can say that the growing bone forms a very dynamic tissue which can respond directly and efficiently on growth and trauma. The periosteum is thick, the cortex is porous, the epiphyses is vulnerable and the whole bone is richly vascularized.

**Biomechanics of Growing Bone**

Bones are subjected to a variety of forces, which induce in the bone tissue a state of deformation and stress. If locally the maximum stress of the
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Fig. 1. Pure tensile (1), compressive (2), and shear (3) stresses are present in specific cross sections of a structure. In an arbitrary cross section (4) the three types occur together.

material, called strength, is being exceeded, the material breaks: a crack propagates through the bone and it is fractured.

To understand how this process is being influenced by the bone mechanical properties and to understand the relevant differences between young and matured bone, some basic mechanical facts need to be considered.

Forces on bones result from various causes, being weights of body parts, acceleration and deceleration of these parts, muscular action, ligament constraints and joint contact. Because children are less heavy than grown-ups and also because their muscular power is less, we can expect that forces on child bones will be less than those on matured bones. This does not mean that stresses in young bones are also less: as we will see, the stress situation is not only dependent on the loading of a bone, but also on its mechanical properties and its geometry.

Stress is defined as an amount of force per unit area; a certain force transmitted over a small area induces a larger amount of stress than the same force transmitted over a large area. The general state of stress in a point of a material is three-dimensional. On an imaginary cross section through the material we find three types of stresses, namely, tensile, compressive and shear stress (fig. 1). The deformation of a material is charac-
terized by its state of strain, being locally defined as the relative dimensional change of a specific length. For instance (fig. 2), if the original distance between two points of a bone is \( l_1 \) and after loading \( l_2 \), then the local strain is defined as \( \frac{L_2-L_1}{L_1} \).

It should be kept in mind that both stress and strain are locally defined phenomena.

Very important for the mechanical behaviour of a material is the relation between stress and strain. This relation is usually evaluated with tension tests on material samples. An example of such a sample is shown in figure 3. This sample is being loaded with a tensile force \( F \) (newtons) from zero up till fracture. We may assume, for this case, a homogeneous stress distribution, being \( F/A \) (N/m²), if \( A \) denotes the cross sectional area in m². While the force rises, the stress rises also, and the sample elongates by an amount of \( \Delta l(\text{m}) \). The strain inside the sample, also homogeneous in this case, will be \( \Delta l/l \), if \( l \) denotes the original length in m. By measuring force and elongation simultaneously during this test, the stress-strain relation, characteristic for the specific material, is evaluated. An example of such a relation is shown in figure 4, a so-called stress-strain curve. Some important material properties are defined using these curves.

Generally in the first part of the stress-strain curve the material will behave elastic, meaning that if the force is released, the material will resume its original shape. In the second part of the curve a material will generally behave plastic, meaning that the stresses result in irreversible deformation.
Technical structures (e.g., bridges, but also artificial joints) are designed in such a way that the stresses in the material will not reach into the plastic region. In normal physiological situations, bones are probably only stressed in the elastic region. At a certain stress value the material fractures; this value is called the **ultimate stress** or **strength** of the material. The strain on fracture is called the **ultimate strain** or **toughness** of the material.

A material with high ultimate strength is called **strong**, contrarily to a **weak** material. A material with high ultimate strain is called **tough**, contrarily to a **brittle** material.

The first part of the elastic region is usually linear, meaning that the stress is directly proportional to the strain. The proportionality constant is called the **modulus of elasticity** or **Young's modulus** (E, N/m²); hence in the linear elastic region we find:

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\text{Stress} = E \times \text{Strain} \quad \text{(Hooke's law)}.
\]

If a material has a high modulus of elasticity, it is called **stiff**, contrarily to a flexible material.
With respect to different types of bone tissue, Evans [1973] has given an excellent review of the above-mentioned properties. Figure 5 gives average values of toughness, stiffness and strength of human cortical bone as function of age, as drawn according to data by Currey and Butler [1975]. From these curves one may conclude that young bone is tougher, less stiff and weaker than matured bone. If, using this information, the stress-strain curves for different age groups would be reconstructed, the results would look like the example in figure 6. Many specific types of fractures in young bone are easily understood if their specific properties are considered. In the Greenstick fracture, for example, the failure is initiated by tensile fracture on one side of the bone; the other side does not fracture, but only deforms plastically. This is due to the superior toughness of the young bone.

Another example is the occurrence of the buckling failure in children. As has since long been recognized in technical disciplines, buckling is not
caused by exceeding the ultimate compressive stress of the material, but by an instability phenomenon. Buckling strength has no relation with compressive strength, but is only dependent on the slenderness of the column, or bone in this case, and the modulus of elasticity of the material. Since the modulus is lower for young bones, these are more vulnerable for buckling.

Until this point we have discussed the local relation between stresses and strains inside the bone material. The amount of stress in a whole bone on which a load is applied, is of course dependent on the geometry of the bone. An example is shown in figure 7: the stresses in the steel rod and in
the bone rod will be identical, because both geometry and loading are equal, the deformation (deflection) of the steel rod will be about 10 times smaller, because the modulus of bone is about ten times smaller than that of steel. The deflection of the bone tube is again smaller than that of the bone rod: although both have the same cross-sectional area, hence are made of an equal amount of material, the geometry of the tube is more favourable. Also the stresses in the tube are lower. The maximum stresses inside the tube and the rod on this kind of loading are approximately proportional to the third power of their outside diameter and inversely proportional to their lengths.

In concluding it can in general be stated that the material strength of young bone is less than matured bone, that the geometrical strength of both young and matured bones is in first approximation proportional to the third power of their outside diameters divided by their lengths, while the applied loads will in first approximation be proportional to body weight. It may be assumed that the different properties work together in such a way, that the bones have, at every age, an equal overall resistance against fracture in normal functioning.

References