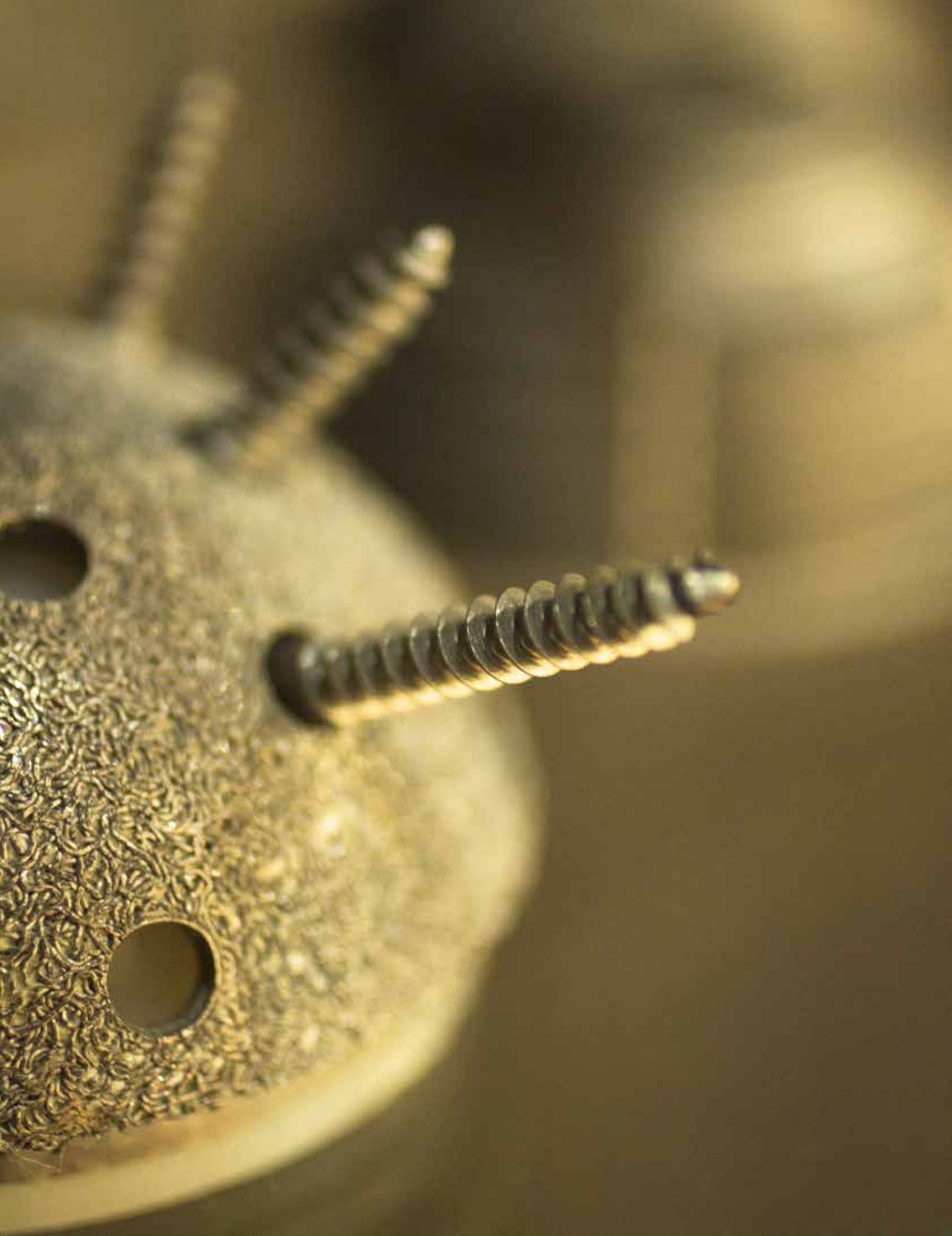


# Biomechanics and Biomaterials in Orthopedic Surgery

Pamela Benavidez, cst

The main objective in any orthopedic procedure is to remediate problems in the skeletal system due to genetic malformation, injury or aging. A key component of a successful patient outcome is the intellectual and technical proficiency of the surgical team. The surgical technologist, therefore, should become competent in the biological and mechanical aspects of bone and the skeletal system, the fundamentals of orthopedic biomaterials and their connection to postoperative implant healing.

## BONE COMPOSITION

Bone is composed of chemical, cellular and structural materials.

A. Chemical composition.

1. Organic material. Organic material in bone comprises approximately 30% of its dry weight.[1] The principal organic component of bone is collagen, which is produced by the bone-forming cells, osteoblasts. Collagen's filamentous structure gives this molecule a flexible characteristic. However, when collagen is mineralized in the bone matrix, it provides strength, stiffness, and thermal stability. The relative orientation of these collagen fibers within the bone matrix is an important determinant of the elastic anisotropic quality of bone.[2]

   Bone tissue also contains citrate, which works as a bridge between packed mineral platelet layers.[3] Bone mineral is linked to the organic matrix through proteoglycans rich in glycosami-

### LEARNING OBJECTIVES

- Review the chemical, cellular and structural composition of bone.
- Learn about the biomechanics of bone and orthopedic implants.
- Understand the fundamentals of commonly used biomaterials.
- Study the implant-to-bone osteointegration process.
- Review the elements needed to enhance bone healing.

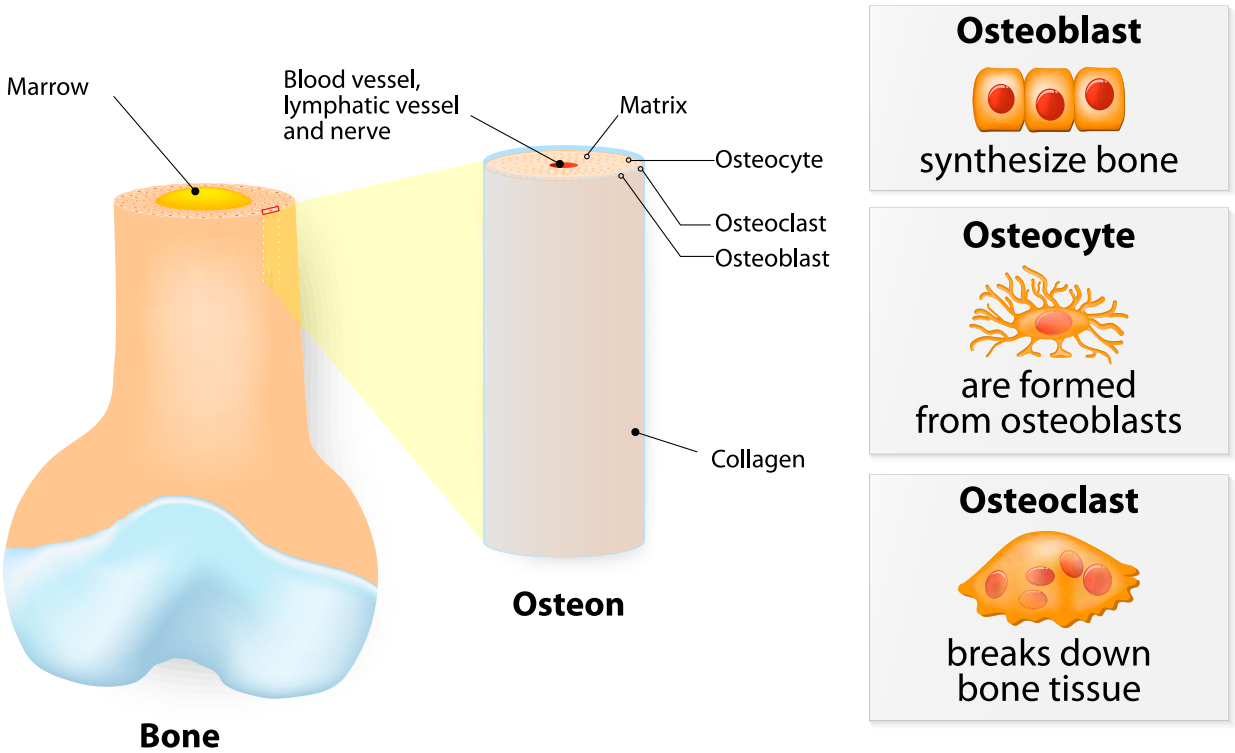
noglycans (GAGs), which play an important role in determining mineral size and crystallinity in bone. A family of proteins called *bone morphogenic proteins* (BMPs) have also been found to reside within the extracellular matrix in the bone. These proteins, structurally and functionally related to transforming growth factors, are responsible for the migration, proliferation and differentiation of bone-forming cells through signal transduction pathways.[4]

2. Inorganic material. Inorganic materials, mainly ionic compounds, comprise about 70% of the bone's dry weight. Bone functions not only as a structural and support tissue, but also as a reservoir for ions such as calcium, phosphorous, sodium and magnesium.[1] Most of the calcium and phosphate found in bone is in the form of hydroxyapatite ($Ca_{10}(PO_4)_6OH_2$). Hydroxyapatite appears in bone as mineral platelets of organized collagen fibers intercalated by hydroxyapatite crystals. While collagen gives bone soft and ductile properties, the hydroxyapatite crystals give it a stiff and brittle character.[5]

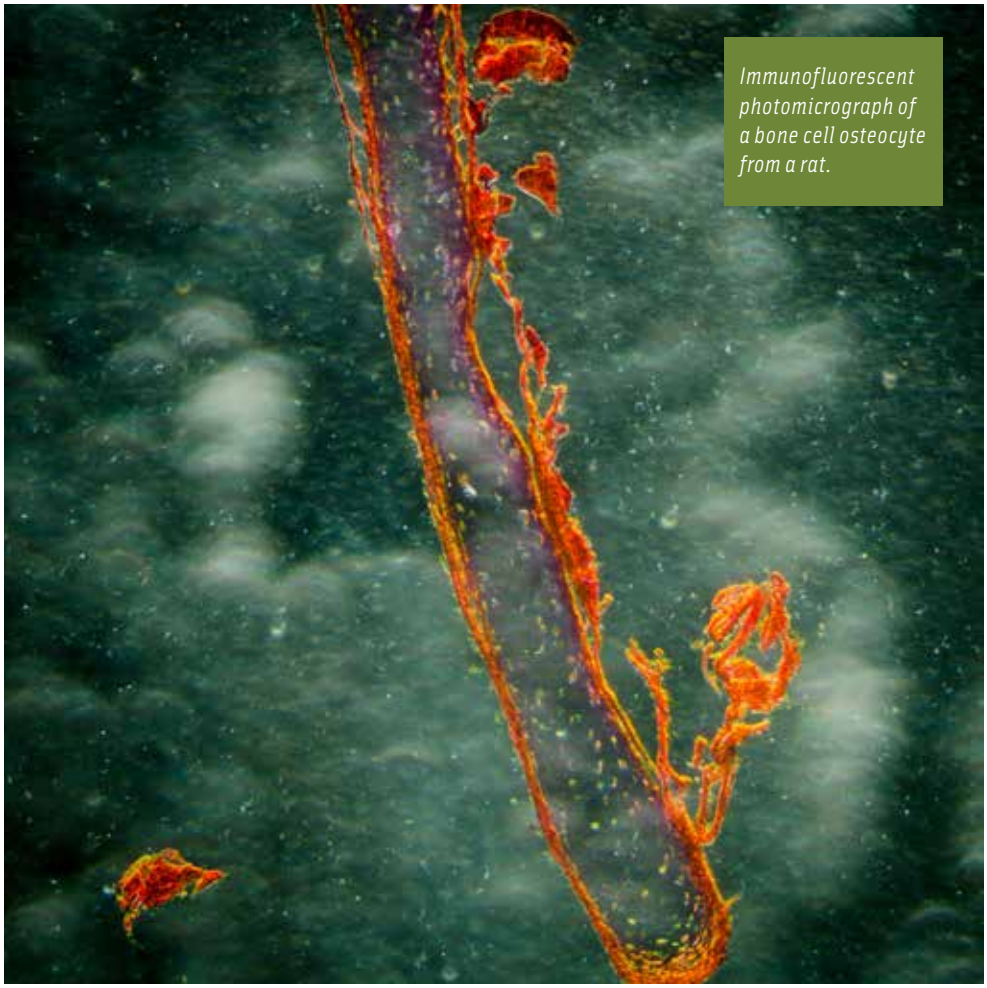
B. Cellular composition.

1. Osteoblasts. Osteoblasts are better known as bone-forming cells. They comprise about 4-6% of bone cells. These cells are in charge of bone production and mineralization through the secretion of polysaccharides, collagen fibers and other factors for osteoclast differentiation.[6] Osteoblasts differentiate from mesenchymal stem cells (MSCs). Differentiation occurs through signal transduction cascades headed by cytokines.[7]
2. Osteoclasts. Osteoclasts are the bone resorptive cells. These cells encompass 1-2% of bone cells and work by secreting acids and collagenolytic enzymes. Stimulation by the receptor activator of nuclear factor-kB ligand (RANKL) generates a cascade of events in a signal transduction pathway that leads to the proliferation of bone marrow macrophages (BMMs), which eventually fuse to each other to become multinucleated mature osteoclasts.[8]
3. Osteocytes. Osteocytes, better known as mature osteoblasts, encompass 90-95% of total bone cells. These cells are found dispersed in a sea of mineralized matrix within lacunas connected by dendritic processes that

# INTERNAL STRUCTURE OF A BONE



radiate to the bone's surface through canaliculi. Osteocytes are believed to function as sensory cells by reacting to mechanical strain through the activation of either bone formation or bone resorption pathways. They belong to the same lineage of osteoblast progenitor cells. However, once osteoblasts differentiate, some of them continue to differentiate into osteocytes.[9]



*Immunofluorescent photomicrograph of a bone cell osteocyte from a rat.*

C. Structural composition.

1. Periosteum. The periosteum is the outer layer that covers most bones. During development, this layer plays an important role in bone growth. However, in adulthood, its main function is in repair and remodeling. There are many structures associated with the periosteum that provide a system for nourishment and communication, such as blood vessels, sensory and motor nerves, and lymphatic vessels.

   The periosteum contains two distinctive layers: an outer fibrous layer and an inner cambium layer. The outer layer contains fibroblasts and collagen fibers that can form a continuous association with joint capsules, tendons, muscle fasciae or epimysium. The inner layer is rich in blood vessels and mesenchymal cells with osteogenic, chondrogenic and osteoblastic potential.[10]
2. Compact (cortical) bone. The main component of the compact bone is the Haversian system or osteon. This structure is composed of different elements that, together, give it a porous character. Mainly composed of collagen and hydroxyapatite, osteons organize in a geometrical way forming a concentric lamellar structure. Newly added layers of collagen and hydroxyapatite converge towards a central vascular space. As the bone remodels, new osteons form, displacing the old ones and forming new vascular spaces. The angle and distance in which these osteons lay depend on the orientation of the collagen fibers that constitute them.[11]
3. Cancellous bone (also known as trabecular or spongy bone). The structure of cancellous bone is highly dependent on mechanical stress. This is why its structure forms a heterogeneous trabecular network of different shapes and thicknesses whose morphology varies by location. Accordingly, the variable structure of trabecular bone allows for elastic resistance to any force applied. Cancellous bone is metabolically more active than compact bone.[12] However, the thickness in the trabecular network has been found to decline with age, which is believed to be due to the decrease in nutrients supplied to the bone.[13]
4. Endosteum. Studies have shown that the endosteum lining is where hematopoietic stem cells (HSC) are made and reside. A comparison of HSC from the bone marrow and the endosteal lining showed that the cells in

the lining proliferate at a higher rate than those of the bone marrow. The study indicates that the endosteum might play a more prominent role on the production of blood and stromal cells.[14]

5. Medullary cavity. The medullary cavity is the space created by the honeycomb cancellous bone and the space within the diaphysis of long bone, where bone marrow can be found. There are two types of bone marrow: red marrow (composed of hematopoietic cells) and yellow marrow (composed of adipose tissue). The ratio of red to yellow marrow varies with age.[15] In adults, only cancellous bone provides a stable supply of hematopoietic cells throughout life.[16]

> The search for materials that can closely mimic bone's physical and mechanical properties is why tissue engineering is an ever-growing field.

## DETERMINATION OF NEED

Many conditions of the musculoskeletal system can be managed noninvasively. However, cases exist for which noninvasive treatments do not provide a remedy to the condition and even others in which a surgical approach is the only option. In general, treatment failure of longer than six months, severe pain that affects the performance of daily tasks, and joint instability or abnormal alignment justifies surgical intervention.[17]

A. Orthopedic trauma. Trauma to the bone can be caused by a shock, a fall or a twist. The fracture generated can be displaced, non-displaced, open (bone is exposed) or closed. Many fractures require reduction and maintenance. Often, reduction can only be accomplished through the use of implants such as screws, plates, rods and other permanent devices. Immediate intervention is required in the case of open fractures, dislocation of major joints and fractures implicating the vascular system.[18]

B. Congenital and degenerative disorders. These disorders may be due to genetic defects, drugs, infections, trauma, anoxia and *in utero* compression. Some of the most prominent congenital disorders requiring surgical implants are:

- *Pseudarthrosis*
- *Skeletal dysplasias*
- *Rheumatoid arthritis*
- *Gout (arthritis urica)*

## BIOMECHANICS OF BONE

In order to study the mechanical properties of bone, the surgical team must be familiar with the physical principles of Young's modulus of elasticity and the anisotropic nature of bone.

A. Young's modulus of elasticity. Even though it is difficult to imagine bone as an elastic material. It could be logically inferred that in order to stand the action of a force without permanent damage, a material must be elastic enough to spread the stress applied in a uniform way. Depending on the direction of the applied force, three main types of forces can be applied to a material such a bone.

- Compression. In compression, all the force vectors point inward perpendicularly to the sample causing a reduction in volume.
- Shear stress. Shear stress is when the force vectors are tangent to the sample's surface, causing a twist motion under constant volume.
- Tensile stress. During tensile stress, two forces act at opposite ends of the sample, either pulling it apart or pushing it inward.

Through a series of experiments based on these physical principles, the English physicist Robert Hooke discovered that, for solid materials, strain (the extent to which an object deforms due to an applied force) and stress (the object's resistance to an applied force) are correlated by a constant that he named Young's modulus or elastic modulus. Eventually, Hooke's principles became a law, which is used today for the study of bone and the development of biomaterials in orthopedics.[19]

Since bone is a heterogeneous and anisotropic structure, its Young's modulus depends on its micromolecular structure, which varies significantly from one point to another within the same structure. In general, the less porous and more dense the bone structure, the higher its Young's modulus constant ($E$).[20]

B. The anisotropic nature of bone. Anisotropic properties are those that vary in their value when measured in different directions. Given the anisotropic nature of bone,

it is not surprising that bone tissue reacts differently at different points in response to a force. Although Hooke's law would predict a linear stress-strain relationship, experiments have shown the prevalence of a nonlinear relationship. Throughout the life of an individual, bone remodels its microstructure based on the load applied. Thus, different points in a single bone can show different stress-strain responses.[21]

## BIOMECHANICAL TESTING OF IMPLANTS

Testing of orthopedic implants prior to market release is an important process that protects patients from implant failure.

A. Computer simulation. Orthopedic implant design has benefitted from the advent of computerized technology. There are many implant prototyping techniques including stereolithography, laser sintering, 3D plotting and 3D printing. These methods make use of computer software, computed tomography (CT) and magnetic resonance imaging (MRI) in a designed virtual environment similar to the one encountered inside the tissue.[22]

   Orthopedic implant models are based on CT scans of Caucasian cadavers.[23] Although there is evidence of ethnic and gender differences on bone strength and geometry, data is limited due to the prohibition of CT scan studies on live individuals, which has halted the study of other population groups.[24] There is a growing movement toward the experimentation with MRI scanning of healthy patients, which has been proven to be less harmful and with similar accuracy to CT scans.[24]

B. Physical model testing. The goal of orthopedic implant testing is to ensure the durability of the implant, validate an improvement over existing implants, and reduce the dependence on animal experimentation.[25] Biomedical simulators are designed to test the mechanical and physiological properties of implants compared to a control. Effects of tension, compression, wearing, impact loading, temperature and fatigue are among some of the variables tested. Simulators allow for the specification of motion-generator points as well as weight-bearing points.

   Physical properties of the implant materials, such as hardness, stress and strain, should approximate the parameters of real bone. Physical testing also takes into account handling processes, such as development, sterilization, storage and implantation.[26]

C. Animal studies. Animal testing is limited due to the fact that animal testing is considered ethically unsound. In addition, orthopedic implants are highly dependent on mechanical functionality; therefore, there is not an appropriate animal model that would correctly replicate human fitting.[25]

Once implants pass through all the required preclinical testing, they follow clinical trials, randomized trials, multicenter studies and implant registry after their market release.[25]

## ORTHOPEDIC BIOMATERIALS

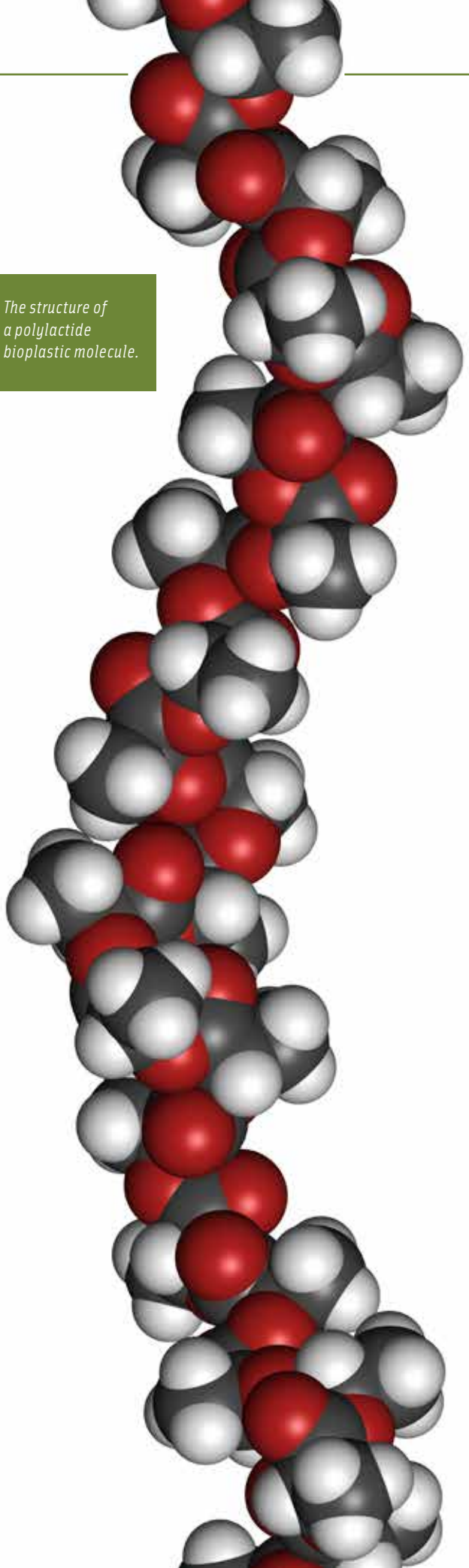
The complex structure of bone poses a challenge for fracture repairs. Even though fixation devices are sometimes the only option available in major injuries, these implants cannot be resorbed and remodeled by the body. Risk of additional fractures and implant failure is also a possibility.

Implant materials composed of actual bone, such as autograft and allograft, may seem a more suitable solution due to their osteoconductive, osteoinductive and osteogenic properties, but also come with disadvantages. In the case of autograft, the additional procedure required for tissue harvesting adds to the possible surgical complications. Allografts present a greater risk due to the increased chance of disease transmission and implant rejection when compared to autografts. The search for materials that can closely mimic bone's physical and mechanical properties is why tissue engineering is an ever-growing field.

Common biomaterials for orthopedic implants include synthetic polymers, naturally derived polymers, bioceramics and metals.

A. Synthetic polymers.
   1. Properties. Most synthetic polymers used on the medical industry are biodegradable in nature. In orthopedics, these polymers can function as drug delivery devices and skeletal support systems. The chemical composition of synthetic polymers can be tailored based on the desired rate of degradation and drug delivery. In general, hydrophilic synthetic polymers degrade faster than hydrophobic (or less hydrophilic) ones. In addition, synthetic polymers with low molecular weights per unit degrade faster than those with high molecular weights.

      Very few polymers are crystalline in nature; however, the more organized the molecular structure of the polymer, the less it is prone to hydrolytic degradation. The shape of the implant also affects its rate of degradation. The higher the surface-to-volume ratio, the faster the degradation rate. In addition,



*The structure of a polylactide bioplastic molecule.*

local conditions such as vascularity, endured stress and movement also affect the rate of degradation and osteointegration.[27]

2. Commonly used synthetic polymers.
   - Poly (propylene fumarate)
   - Poly (p-dioxane)
   - Poly (1 5-dioxipian-2-one)
   - Poly (trimethylene carbonate)
   - Poly (lactide-co-glycolide)
   - Septacin® (control-release polymer)
3. Pros and cons. Prosthetic devices made of degradable synthetic polymers offer numerous advantages. One of these advantages is slow drug delivery. Even more important is the advantage it offers in bone healing. Contrary to nondegradable implants, degradable synthetic polymers do not require a second surgical intervention for removal. Instead, they allow the slow transfer of load stress from the degrading implant to the healing bone. Synthetic polymers also offer more variety and less probability of immunologic reactions.[28]

   Among the negative aspects of these implants are foreign body reactions and fibrous tissue formation, which lessens as the material degrades. In addition, some degradable synthetic polymers may contain acidic components that stimulate inflammation as they are released. Synthetic implants have lower strength than metals, which makes them less suitable for patients with known ossification problems or for cases when the implant is expected to sustain great loads.[28]

B. Naturally derived polymers.
   1. Properties. Naturally derived polymers share some common features with synthetic polymers, such as its biodegradability and biocompatibility. They also possess a structure that better mimics bone matrix and often contain properties that aid in cell attachment, proliferation and differentiation. These polymers have a complex structure that can better adapt to existing bone tissue.[29]
   2. Commonly used natural polymers.
      - Alginic acid
      - Hyaluronic acid (HA)
      - Chondroitin sulfate
      - Collagen
      - Gelatin
      - Fibrin
   3. Pros and cons. The most significant advantage of naturally derived polymers is their ability to adapt and mimic the natural matrix. As with synthetic polymers, the successful integration of these polymers requires no further surgical interventions. Natural polymers also have less probabilities of causing toxicity. However, certain molecules and contaminants in these polymers may elicit an immunologic reaction. In addition, the processing of naturally derived polymers is more difficult, and transfer of pathogens to the recipient is more likely. It is also challenging to determine the outcome of their implantation, since there is a wide variability among natural polymers of the same class.[28]

C. Bioceramics.
   1. Properties. Bioceramic materials are polycrystalline inorganic compounds, including glass products, made out of metallic and non-metallic elements with highly organized crystal arrangements. Metallic oxides, calcium sulfates and nitrites are among the most commonly used compounds in the development of ceramic implants. The compatibility of bioceramics is due to the inertness of the molecules that compose them; however, some may have a certain degree of reactivity. They can be classified as bioactive, if they possess osteoconductive and drug delivery properties; or bioinert, if they do not elicit a reaction when introduced in biological tissues.

      Bioceramics are brittle with low tensile strength and high compressive strength; therefore, are commonly used in locations were high compressive strength is required, such as on acetabular cups or femoral heads.[30] Bioceramic materials vary in their porosity according to their crystal structure. Although dense materials are ideal for high mechanical load resistance, porous bioceramics allow for osteointegration.[31]
   2. Commonly used materials.
      - Calcium Phosphate (hydroxyapatite)
      - Alumina
      - Zirconia
      - Tricalcium phosphate
      - Barium sulfate (bone cement)
   3. Pros and cons. Bioceramics are highly biocompatible. Porous types also allow the incorporation of bone healing enhancers. However, since the research and their production is costly, fewer options are available compared to other biomaterials. The brittle characteristic of bioceramic materials limits the anatomical location where they can be implanted. Those that offer good mechanical strength usually show poor osteointegration.[32]

D. Metals.
   1. Properties. Metal implants are the most resistant of all biomaterials. Metals are ductile, which allows for the spread of stress forces without deformation. Thus, metal implants are usually used in locations were high mechanical strength is required. Implants of the same type of metal show a pattern of heterogeneity in their characteristics from the influence of design on the material properties.

      Because of the tendency of metals to form ions in solution, selection of the type of metal during implant design is based on its reaction in biological systems.[32] However, metal implants available in the market show high resistance to corrosion and great biocompatibility.[33] Metallic biomaterials are neither good osteoconductors nor good osteoinductors; nevertheless, bioengineering technology has designed metallic porous coatings for metal implants facilitating their osteointegration.[34]
   2. Commonly used materials.
      - Titanium-based alloys
      - Stainless steel
      - Cobalt-chromium alloys
      - Titanium
      - Nitinol
      - Tantalum
   3. Pros and cons. The most important advantage of metal implants is their long-term mechanical resistance. In addition, metal fixation devices offer the most reliable support for the healing fracture. However, one of their drawbacks is poor osteoconduction. In addition, because of the tendency of metals to form oxides, metal implants tend to corrode.[33]

      Inflammatory response around the implant is also a possible complication, which can cause bone resorption and subsequent loosening of the implant. Fracture fixation with metal implants requires additional surgical interventions for either removal or replacement, which impose additional risks to the patient. Aseptic loosening is an inevitable consequence of wearing that requires substitution for a larger implant. Although it is not clear how metal ions affect osteoclast activity, it has been shown that metal ions decrease the proliferation of osteoblasts.[33]

Since not one single material can mimic the intricate structure of bone tissue, many orthopedic implants are a combination of several biomaterials and other bone healing enhancers, which may better promote vascularization, osteogenesis and tissue repair.[35]

## IMPLANT-BONE OSTEOINTEGRATION

Implant osteointegration depends on the region of bone in which the implant is located. Epiphyseal and metaphyseal osteointegration occurs faster than diaphyseal osteointegration due to the increased vascularity and therefore fast remodeling rate at the end of long bones. In addition, mechanical strength of the lower extremities is higher than in the upper extremities. Osteointegration can be mechanical, where the bone remodels around the implant and a layer of collagen forms between the two surfaces, or

ongrowth, during which implant affinity allows the bone to grow within the implant.

The size, shape, texture, type of material and physical properties of the implant also influence osteointegration. To attain the best integration, implants should be of equal or higher elasticity than the bone tissue that surrounds them. When rigid material is implanted on a more flexible area, additional materials that aid osteointegration, such as bone cement, ought to be employed. In the case of osteoconductive and osteoinductive materials, osteointegration occurs without the development of a collagen layer. Indeed, the spread of the stress throughout the implanted joint and its bone when a force is applied is greater in ongrowth implants than in mechanically fitted implants.[36]

*Imagine how the texture of this titanium metal hip implant would aid osteointegration.*

A. Requirements for a well-engineered implant scaffold. Any engineered implant must possess characteristics common to bone. These characteristics would either allow the implant to last for the life of the individual or support the fracture until complete healing has been accomplished.[37] A well-engineered implant should have the following characteristics:
   1. Osteoconduction. It allows the ingrowth of blood vessels and invasion of osteogenic cells.[37]
   2. Osteoinduction. It stimulates the differentiation of stem cells into osteogenic cells.[37]
   3. Proper fit (stability). The size of the implant should be proportional to the size of the bone. Bone-implant contact should be ensured to facilitate osteointegration and stress dispersion.[37]
   4. Ductility (Elasticity vs. rigidity). This property confers a certain degree of flexibility in order to allow the implant to shape into the bone.[37]
   5. Texture. Implants can be polished, smooth blasted or rough blasted. Smooth surfaces are not osteoconductive; instead, they induce the formation of a collagen layer between the implant and the bone. Rough surfaces on the other hand facilitate osteointegration.[37]
   6. Resistance to fatigue. Implants are meant to either endure stress until the healing process has completed or for the rest of the life of the individual. Implants with low resistance possess a high risk for fracture on the same site.[37]

B. Factors affecting implant-bone osteointegration. Many times it is not desirable for fixation devices such as plates, screws, and pins to integrate because of intended removal. However, for those devices in which healing depends on osteointegration, it is very important for the tissue conditions to be optimal. Certain factors can interfere in this process:
   1. Infection. Due to the artificial nature of implant materials, they are always at risk of exogenous infections. An infection affecting an implant can start as a localized point and spread as a biofilm. The rate of infection is faster in nonintegrated areas, joints and on implants that integrate by formation of a collagen layer. If the infection is introduced during the procedure, integration does not occur. Granulation tissue forms around the infected areas, which stimulates osteoclastic resorption of bone around the implant. Antibiotic therapy and replacement of the infected implant is often necessary.[37]
   2. Aseptic loosening. Many times, an inflammatory response occurs without the presence of infection due to the implant material particles being removed by macrophages. Inflammatory events attract cytokines and chemokines to the infected area and stimulate the

proliferation of osteoclasts. Osteoclasts cause loosening of the implant by resorbing the bone around it.[37]

3. Implant allergies. This is a controversial issue that has not yet been unanimously supported. Studies have found a small percentage of patients with implant failure showing signs of contact dermatitis. Tissue inflammation around the implant, which causes loosening of the implant, and skin lesions one year after the surgery have been observed. Some researchers agree that there is a need for presurgical screening for allergies. Others believe that the population of patients manifesting allergic reactions to the implant is so small that it does not justify regular screening.[38]

C. Enhancing bone healing. Implant osteointegration is a process that requires the right conditions in order to occur. The first few weeks following the surgery is the most critical time; when the implant is most prone to failure as integration is just starting to take place. Stabilization highly depends on osteointegration; therefore, the faster it occurs the lower the chance of implant failure. Bone healing enhancers catalyze integration by providing the necessary elements needed for bone healing.

1. Growth factors, hormones and other osteogenic compounds. Growth factors are signal molecules that stimulate the proliferation, recruitment and differentiation of mesenchymal cells into osteogenic cells.[39] Growth factors also stimulate angiogenesis and granulation tissue formation.[40]

   Parathyroid hormone (PTH) is another protein that has been used as a bone healing enhancer. PTH controls calcium homeostasis by regulating the osteoblast-osteoclast activity in bone. This type of hormone therapy is especially used in osteoporotic patients, for which fast fracture healing is paramount.[41] There are many other products in the market that promote osteogenesis such as bone morphogenic proteins, which is a family of proteins commonly used in spinal fusion due to their osteoinductive properties, and oxysterols, which are a group of osteogenic and anti-adipogenic compounds.[42]

2. Bone-marrow-derived mesenchymal cells. Bone-marrow-derived mesenchymal cell therapy is frequently used in cases with non or delayed union. Randomized studies have shown the significant benefits of stem cell therapy, such as a reduction of up to half the healing time compared to control. One of the technical issues regarding the studies on bone-marrow-derived mesenchymal cells as a therapy option is the certainty with which it can be determined that the osteogenic cells involved on the healing process are derived from the therapeutic agent and not from the patient's bone marrow.[43]

## CONCLUSION

The nature of bone, as both a composite and a dynamic living structure, dictates its mechanical properties and its behavior in response to injury. However, many injuries and/or conditions require a surgical approach in order to promote correct bone remodeling. The experimental study of the structure and composition of bone has led to the development of orthopedic implants that allow osteointegration to otherwise irreparable injuries. The surgical technologist should become proficient in the areas of bone biology, orthopedic biomechanics and orthopedic biomaterials in order to identify the appropriate prosthetic materials and healing enhancers for the surgical patient.

## ABOUT THE AUTHOR

Pamela Benavidez, CST, was born in Venezuela and graduated from ERWIN Technical Center in Tampa Bay, Florida. She currently works as a CST in the Tampa Bay area and holds a bachelor's degree in integrative animal biology from the University of South Florida (USF). During her bachelor's studies, she joined two research projects, one of which was presented during the 2014 USF Undergraduate Research Colloquium. Benavidez is also a member of the Corpus Christi Medical Mission, where she has had the opportunity to help the underserved community of Dilaire, Haiti. She is currently pursuing her goal of becoming a doctor.

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