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Mechanical Properties of Artificial Materials for Bone Repair

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Abstract: Bone defect caused by injury, infection, tumor and congenital diseases is one of the most common diseases in clinical orthopaedics. Bone grafts are necessary when self-healing is not effective during the recovery. Preparation of ideal bone substitutes with good biocompatibility and biodegradability to repair bone defects has become the focus. So far artificial materials used in hard tissue repair and reconstruction most notably are metals and their alloys, then the ceramic materials and their composite materials. From the perspective of mechanical properties, metals have some advantages, but corrosion issue and stress shielding of metal have baffled scientists through the age and have been long searched for solution. The elastic modulus of ceramic is more close to the natural bone compared to metal while the improvement of brittleness has been always the emphasis for clinical use. Therefore, development of materials of proper mechanical properties without affecting biological compatibility has become a significant subject.
Key words: metal, ceramic, composite, mechanical property, bone
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0 Introduction

Bone fracture and bone tissue injury are big medical problems. An estimated 6.2 million bone fractures occur annually in the United States and about 500 thousand would choose to take bone transplant surgery. The current bone repairing technology mainly includes autogenous iliac crest graft and allograft. In this 500 thousand people, approximately 350 thousand took autograft and 150 took allograft[1-3]. Autogenous bone grafting is considered as the gold standard in the management of bone defects. But this form of transplantation would damage the tissue structural integrity of the body which adds to patients' sufferings. Furthermore the source of autogenous bone is limited and cannot meet enormous clinical need. Allograft as another alternative although relatively abundant may trigger a patient's immune system into launching an attack. There are still many people who cannot get treated properly due to the limited conditions (the quantities of bone products provided, finance, safety, etc).

Bone, now well studied, is known to be a complex and necessary composite tissue in human body, containing many individual constituents. They support and protect the various organs of the body, produce red and white blood cells and store minerals. The elastic modulus of human bone is between 4.6 to 20 GPa[4]. According to the structure, bone is divided into cortical bone and cancellous bone. Mechanical properties of cortical bone are: elastic modulus of 16—20 GPa, and ultimate strength of 30—211 MPa. Mechanical properties of cancellous bone are: elastic modulus of 4.6—15 GPa, and ultimate strength of 51—193 MPa. The density of cortical bone is about 1 990 kg/m^3 and cancellous bone is lower than it but more elastic. Cortical bone grafts are used primarily for structural support, and cancellous bone grafts for osteogenesis.

For centuries, one goal of medical specialists has been the creation of a viable substitute to repair bone. Through the ages, substances such as leather, noble metals, plaster of paris, directly transplanted hard tissues from other species, and other hard substances have been used in an attempt to repair bone tissues. The existing bone substitute materials can be divided into natural materials and artificial materials according to their sources. Natural materials such as collagen, fibrin, chitosan, and chitin have been widely used due to their unique advantages. Artificial materials can be further subdivided into metal, ceramic and polymer according to their different compositions. An ideal bone-grafting material should be able to produce bone by osteogenesis, osteoinduction, and osteoconduction. The substitute materials for repairing bone should have the

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following characteristics: ① good biocompatibility and high bioactivity; ② adjustable speed of degradation and absorption; ③ imitation in composition, structure and shape of natural bone; ④ suitable surface morphology for cells' adhesion, proliferation and differentiation; ⑤ equivalent to or better mechanical properties than those of natural bone. We will focus on the last item.

1 Clinical Artificial Bone Materials

1.1 Metal

Metals have a long history of application in the field of biomedical materials. Noble metals like gold, silver and platinum were the earliest widely used metals in clinical treatment because of their good processability and chemical stability. At the beginning of the 1920s, stainless steel has been exploited for the extensive potential applications in medical science. In 1937, cobalt-chromium alloy was applied to skeleton surgery successfully. In the 1950s, titanium alloy appeared in clinical trials. In the 1970s, the invention of shape memory alloys opened up a new research direction for biomedical material. Besides, tantalum, niobium and zirconium are also important parts for biomedical researchers.

In the application of biomaterial, the majority of stainless steel is austenite in which typical products are 302, 316 and 316L stainless steels. These kinds of steels ensure sufficient corrosion resistance, outstanding processing performance, and satisfactory mechanical properties so that they have been widely used for producing artificial joint. Especially 316L stainless steel is very recommended as implant material by the American Society for Testing and Materials (ASTM). The density of stainless steel is about $7.9\,g/cm^3$ and its elastic modulus is about 186 GPa. The annealed condition represents relatively lower ultimate tensile strength (490—690 MPa), while after cold working or cold drawing the value could be doubled or even more. Considering the issue of nickel sensitivity to human body, nickel-free stainless steel with superior mechanical properties and better corrosion resistance is definitely more popular than traditional ones[5].

ASTM suggests four kinds of cobalt base alloys that can be used as surgical implant materials: F76, F90, F562 and F563. At present, only as-cast F76 and forged F562 cobalt base alloys are widely applied to the production of implants and they mainly serve in the long-term implantation position where demanding bearing force and high corrosion resistance are required. Ultimate tensile strength of casting state medical cobalt base alloy is more than 700 MPa. Extruded alloy after deformation obviously refines grains, the virtual elimination of as-cast alloy leaves shrinkage, and thus mechanical properties are significantly improved. However, the elastic modulus of cobalt base alloy (about 230 GPa) is much higher than stainless steel's, and it does not match the mechanical property of bone, thus cobalt base alloy would lead to an adverse impact on human body implantation.

As biomedical materials, the biggest characteristic of titanium (Ti) and titanium alloys is high specific strength. The elastic modulus of commercially pure Ti is about 110 GPa, which is closer to bone tissue and helps to overcome the mechanical incompatibility with bone compared to stainless steel and cobalt base alloys. Elements such as oxygen, nitrogen and carbon can raise the strength of Ti, but at the same time the ductility decreases. Hydrogen absorbing of Ti easily occurs and hydrogen embrittlement would result in the premature invalidation of materials. When aluminum and vanadium are added to Ti in only a little quantities, the strength of the alloy will be much enhanced over that of commercially pure Ti. These two forms of Ti are the most commonly used in clinical: commercially pure titanium (Ti-160) and an alloy of Ti6Al4V (Ti-318). Ultimate tensile strength of Ti6Al4V is approximately 860 MPa while commercially pure Ti has lower strength, which makes Ti6Al4V attractive for use in high stress-bearing situations[6]. For the implantation use, fracture, friction and wear should be considered because they are important aspects of the behaviour of the implant material.

Ni-Ti shape memory alloy is the most applied shape memory alloy in a clinical context. The tensile strength of Ni-Ti can be gained more than 980 MPa. In addition, the shear strength and fatigue strength are obviously better than those of 316L stainless steel, as well as the wear resistance. Also the study of Chu et al.[7] showed that Ni-Ti shape memory alloy by combustion synthesis has a high ultimate compressive strength (up to 208 MPa) and a low elastic modulus (2.26 GPa), which is similar to that of the cancellous bone and far lower than that of most traditional solid biomaterials. Just like stainless steel, nickel-free steel maintains the trend for evaluation in humans.

Tantalum (Ta), niobium (Nb) and zirconium (Zr) have also been studied and used as implant materials. It has been reported that these metals possess good biocompatibility for biomaterials. The mechanical properties of these three metals are given in Table 1. The clinical studies indicate that porous tantalum (Fig. 1) has excellent biocompatibility and the decreased elastic modulus (2.5—3.9 GPa) matches the natural bone better[8]. Niobium has similar application with tantalum in medicine and zirconium can replace pure Ti for both have almost the same function. But the high cost restricts their extensive application.

1.2 Ceramic

Ceramic material applied in medical field can be traced back to the 18th century, but the systemically basic research and clinical application began merely forty years ago. In the year of 1969, Professor Hench in

Table 1 Physical properties of tantalum, niobium and zirconium

Implant materials	Melting point/°C	Elastic modulus/GPa	Ultimate tensile strength/MPa	Yield strength/MPa	Implant position
Ta[8,10]	2 996	186	207—517	138—345	Acetabulum, tibia
Nb[10]	2 468	108	300—1 000	275	Intramedullary nail
Zr[11]	1 852	88	230—250	210	Femur

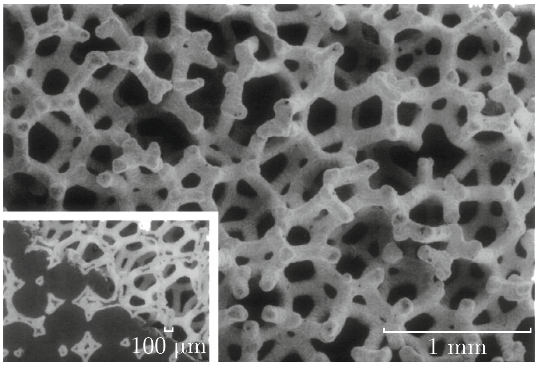

Fig. 1 Scanning electron micrograph of porous tantalum[9]

University of Florida devised bioactive glass[12] which is now widely used in the field of medicine for its excellent biological compatibility. Since then, hydroxyapatite (HA) ceramic, aluminium oxide ceramic and tricalcium phosphate have been studied. Ceramic is superior to metal in strength, hardness, elastic modulus, wear resistance and corrosion resistance, however inferior in toughness leaning to brittle fracture.

HA is the main inorganic mineral component in animals and human bone, which accounts for nearly 60% sclerotin of bone. After implanted in the human body, HA can be combined closely with the hard and soft tissue of the body in a short time, thus it makes HA as the most popular bone graft substitute. Many methods apply to preparing the HA powders, such as solid state reaction, precipitation, sol-gel and hydrothermal method[13]. The mechanical property of HA has a great relationship with the process procedure. The elastic modulus of HA is between 40 and 90 GPa. And the tensile strength and bending strength of dense bone are about 100 MPa and 160—180 MPa, respectively, while come to 120 MPa and 60—100 MPa for dense HA[14]. The study of Jarcho et al.[15] showed that the strength of hydroxylapatite in dense polycrystalline form is related to not only the grain size but also its porosity. The best material in their experiment had an average compressive strength of 917 MPa, and polished samples had an average tensile strength of 196 MPa. Woodard et al.[16] found that different scale porosity of HA induced not only different relative osteoconductivity but also different strength and stiffness. By studying microporous (MP) scaffolds and non-microporous (NMP) scaffolds (Fig. 2), they concluded that bone formed only in scaffolds containing microporosity. The main disadvantages of HA are of high brittleness and low resistance to fatigue so that it can only be used in low or non-load bearing situations or compressive load situations in solid or powder form, such as bone restoration and augmentation, middle ear repair, vertebral and iliac crest replacements. Nanometer hydroxyapatite shows a series of specific characteristics. With the reducing of grain size, the hardness and elastic modulus of nano HA are notably improved, which is helpful for enhancing the mechanics performance of biomaterials as implants.

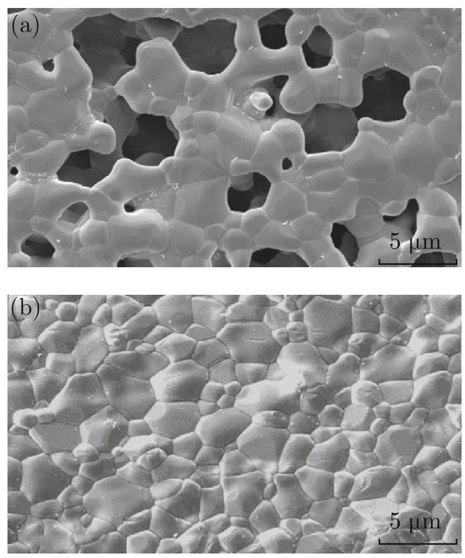

Fig. 2 Scanning electron micrograph of the surfaces of rods in MP (a) and NMP (b) scaffolds[16]

As early as 1920, Albee had advised taking bioabsorbable β-tricalcium phosphate (β-TCP) as a kind of endosteal implant[17]. However, large-scale investigation on bioabsorbable bone replacement materials didn't begin until the year of 1970. Gypsum is the earliest used biodegradable ceramic. It has good biocompatibility but too quick absorbing rate that does not match the formation speed of fresh bone tissues. Nowadays, widely used biodegradable ceramics are a series of calcium phosphate ceramics and β-TCP. In the field of artificial composite bone, β-TCP is meant to provide an osteoconductive scaffold stimulating new bone formation, and the application of β-TCP can be diversified. Improving chemical methods by combining mechanical process or increasing the strength of raw material like adding polylactic acid (PLA) to β-TCP is an effective way to achieve high strength. Peter et al.[18] designed a study that varying content of the reactants influenced poly(propylene fumarate) (PPF) and β-TCP phosphate injectable composite scaffold, and that increasing the PPF/N-vinyl pyrrolidinone ratio would raise both the compressive strength and the compressive modulus of the composites where β-TCP was thought to play a crucial role in composite reinforcement. Research on hydroxyapatite-tricalcium phosphate (HA-TCP) scaffolds[19] modified with the poly(lactic-co-glycolic acid) (PLGA) coating indicated that PLGA incorporation in the HA-TCP scaffolds significantly increased the compressive strength and decreased the residual compressive strength after the quenching testing.

Unlike inert bioceramics and absorbable bioceramics, bioglass is surfactant material that it can bond to bone or soft tissue. Biological activity depends on the composition of the material and it has been revealed by test that the bioglass greatly prompts the bonding strength between implant and surrounding hard tissues. In addition to excellent bioactivity, outstanding designability and adjustable function are also its advantages. For example, after adding fluorophlogopite and apatite into glass phase, the cutting performance of the material is improved significantly while maintaining biological activity. The crystallization of bioactive glass makes the mechanical properties improved dramatically with a little reduction of its bioactivity[20]. The adhesion of common bioglass combining with bone tissue is usually larger than the inner adhesion of bioglass or bone. When testing the bonding strength of tissue and bioglass, fracture often occurs in the interior of the bone tissue or bioglass rather than the interface of their combination. The basic components in majority of bioactive glasses and glass-ceramics that are made by traditional high temperature melting, casting and sintering are SiO_2, Na_2O, CaO and P_2O_5. The first and most in-depth studied composition is 45S5 bioglass, which contains 45% SiO, 24.5% Na_2O, 24.5% CaO and 6% P_2O_5 (with mass fraction). The bending strength and elastic modulus are about 40—60 MPa and 30—50 GPa, respectively[21]. Apatite/wollastonite glass-ceramic (A/W glass-ceramic) is another kind of common bioglass. It can be used to produce artificial vertebrae and ribs. The content of P_2O_5 has a great influence on the mechanical properties of A/W glass-ceramic[22]. The decrease of P_2O_5 (which leads to the increase of wollastonite content) increases the diametral compression strength values. And the surface defects make a great contribution to the strength values. Also the replacement of P_2O_5 by SiO_2 increases the indentation fracture toughness values of glass-ceramics changes. The wollastonite phase with a fibrous morphology may enhance the fracture toughness by several mechanisms.

Aluminium oxide ceramics were used in the medical field for the first time in 1969. Since then, there were over 200 million aluminium oxide joints and 300 thousand aluminium oxide acetabulum that had been used in total hip replacement. At that time a certain quantity of implants failed in the body after grafting due to unreasonable design of operation procedure and problems of material itself (like the heterogeneity of grain size, residual porosity). The properties are greatly enhanced by eliminating cracks and improving the size and distribution of the grain. In addition, hot isostatic pressing process also reduces the porosity of alumina ceramics effectively, increasing its densification degree. The aluminium oxide for medical use should be conformed to the corresponding standards (ISO64749 and ASTMF60310). The bending strength and compressive strength of medical-grade aluminium oxide can reach to 0.5 and 4.1 GPa, respectively. Aluminium oxide ceramic offers excellent chemical stability, resisting attack by most corrosive agents, except hydrofluoric, phosphoric, hydrochloric and sulfuric acids. And the hydrophilic character makes it form water films easily on the crystal surface. Some people think that the good frictional performance may be related to this film.

1.3 Composite

Due to the brittleness of inorganic materials and poor strength of organic materials, a single type of organic and inorganic materials is hard to meet the strict mechanical requirements of bone grafting materials, while composite materials can keep its original composition and at the same time create synergistic effects, acquiring some characteristics that don't have previously. In that case, organic-inorganic composites have been a new type of brisk bioactive materials with mechanical properties analogous to those of the natural bones; β-TCPs mixed with PLA, PPF, and HA-TCP coated with PLGA mentioned above are all well designed and function perfectly as composite implantation. Poly(ε-caprolactone) (PCL) possesses good biocompatibility, high flexibility and bone inductive potentiality, which is advantageous for repairing bone defect while poor hardness and bad hydrophilicity restrict its clinical use. Preparation of a uniform nanostructured PCL-silica xerogel fibrous membrane via electrospinning provides a potential application for bone regeneration. The tensile strength and elastic modulus of the membranes are significantly improved with increasing silica mass fraction (Fig. 3)[23].

The study of Moore et al.[24] showed that a sintered HA-TCP ceramic, when mixed in a 50% : 50% mass ratio with autogenous cancellous bone grafts, was biocompatible and able to provide a scaffold for the ingrowth of bone, and also it is comparable with

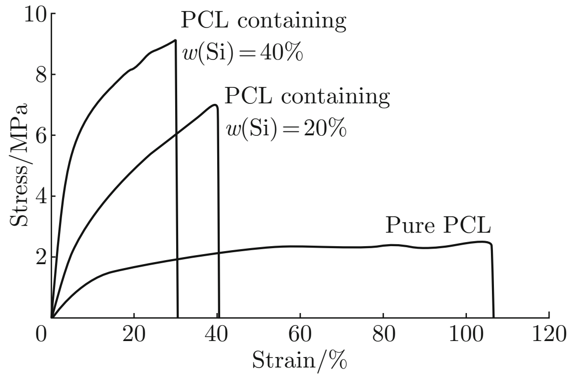

Fig. 3 Stress-strain curves of different compositions with PCL and silica[23]

autogenous bone grafts in filling defects. The parameters of HA-TCP like ratio, porosity and particle size have an effect on the mechanical response of the material. Verdonschot et al.[25] varied these parameters to investigate the time-dependent deformational behavior and drew the conclusion that their mechanical behavior was drastically different from that of the human graft material. Pure HA-TCP ceramics showed poor sinterability due to the phase transformation of β-TCP to α-TCP. After MgO as dopants incorporated into the β-TCP preferably, the mixture represented high density without any phase transformation at the temperature below 1 300 °C for it increased thermal stability of β-TCP. The proper amount of MgO doping increased the mechanical properties obviously without altering the biological safety and biocompatibility of the original composite[26]. Gong et al.[27] studied the effect of the modification of HA surface on mechanical properties. The surface of the HA particles was modified by styrene via in-situ polymerization. Then the processed HA was compounded with high impact polystyrene (HIPS). The coating increased the compatibility between HA and HIPS, so the even dispersion of HA in the matrix ensured the enhancement of interfacial adhesion of the two elements. Thus their stiffness, tensile strength and notch impact strength are improved at the same time. Silva et al.[28] believed that the addition of a particulate zirconia phase to hydroxyapatite probably led to an improvement of the mechanical properties of this kind of composite, as partially stabilized zirconia had been well studied with high strength and fracture toughness. The results demonstrated that values of ultimate compressive strength, elastic modulus, micro-vickers hardness and Poisson's ratio were close to those of human cortical bone, which means these materials present potential applications as structural implants. The ceramic matrix composites will definitely still be the important direction to strengthen the toughness of the ceramic material. It is also the key point to figure out the mechanism of the action how the implants work with the bone in their surface.

2 Prospective

Being a country with the largest population, China will absolutely have considerable market prospect in bone tissue engineering. With elucidation of the bone regeneration and repair process, more efficient materials will be engineered with no doubt.

Developing bone grafting bioactive materials that possess corresponding mechanical properties and biodegradation rate would be always the researchers' pursuit whenever in the past or future. Certain new technologies like nanotechnology and 3D printing of biomaterials[29] incorporated with tissue engineering may provide new sights for linking.

3 Conclusion

It will be the ideal circumstance that the mechanical properties of bone substitutes are close to those of real human bone. But in consideration of too high strength of metal and brittleness of ceramic, the present artificial materials are rarely complete in conformity with human bone. So novel composite materials may be a solution to the problem. Breakthroughs in fabrication techniques and new materials must be developed.

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