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Nanoparticles of Alumina (Al_2O_3): An Overview and Their Applications in Medical Surgery

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Abstract

This article discusses the composition, structure, mechanical properties, and biological applications of alumina (Al2O3). Implants are made of single crystal sapphire or high-density, high-quality polycrystalline aluminium oxide. The principal sources of high-purity aluminium oxide are organic corundum and bauxite. Like any other component, the mechanical characteristics of polycrystalline alumina are mostly governed by grain size and porosity distribution. The fatigue intensity of alumina could be enhanced above the critical pressure because of the presence of liquid, which slows subcritical crack growth. Alumina has substantial advantages over other products in biomedical applications due to its high inertness, which leads to superior biocompatibility and tissue non-sensitization. The higher compressive strength than tensile strength allows it to be more efficient for compression load just like artificial joints and teeth. Some attempts have been made to cover steel substrates with alumina to take advantage of its excellent biocompatibility and resistance to metal oxidation.

Keywords: Polycrystalline; Biocompatibility; Bauxite; Organic; Pressure; Oxidation.

Introduction

Aluminum oxide (Al_2O_3), often known as alumina has been used as a material for prostheses and surgical device components since 1970. It is an inert component with good corrosion resistance in an *in vivo* environment. It causes only a minor reaction in the tissue and is stable for many years. It can be found in Topaz (Al_2SiO_4 (F, OH)$_2$) and Emerald ($Be_3Al_2(SiO_3)_6$), as well as ruby and valuable sapphire gemstones. The Bayer process is used in industry to separate it from ores such as cryolite and bauxite. Alumina is commonly thought of essentially an abrasive because of its hardness in addition to high melting temperature as a impliable component, aside from its use in prosthetics and surgical instruments [1,2]. Bauxite is used to make alumina industrially via Bayer method. There are three stages to this [3,4].

- **Separation:** Bauxite aluminum-containing minerals are separated from insoluble substances through dissolving them in sodium hydroxide.

$$(OH)3+Na++OH-\to Al(OH)-4+Na+....(1)$$

- **Accumulation:** Crystalline aluminium trihydroxide is accumulating. That is the polar opposite of the isolation stage, with the exception of regulated chemistry.

$$(OH)_4+Na^+\to Al(OH)_3+Na^++OH^-....(2)$$

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- **Calcinations:** Aluminium hydroxide $Al(OH)_3$ is calcined on the way to produce alumina. In order to form alumina, water is forced away. This procedure determines the qualities of the final product.

$$2(OH)_3 \rightarrow Al_2O_3 + 3H_2O \ldots.(3)$$

Aluminum oxide (Al_2O_3) generated through Bayer technique is re-crystallized depending on product for which it could be utilized. Al_2O_3 can be found in a variety of crystal phases conditional on the heat-treatment environment. α-alumina has a high density, is non–porous, and is nearly inactive. It is exceedingly durable in addition to scratch-resistant. It offers good corrosion resistance in various ways depending. The porosity and purity of the alumina surface determine strain as well as crack resistance, and these factors influence the ultimate qualities [5]. Alumina, on the other hand, is exceedingly wettable, resulting in a low coefficient of friction. An outer alumina layer absorbs water and biological materials, resulting in exceptional wetting capabilities. Only when the roughness is a little below 0.02 µm, in other words the grain size is less than 4 µm with a very tiny size range, will alumina have a weak resistance as well as wear coefficient. Broad grains will be exposed if the surface roughness exceeds 0.02µm, contributing to extremely quick load-bearing surface wear [6]. The mechanical characteristics of 99.5 percent pure alumina are listed in Table 1.

Table 1: Alumina mechanical characteristics (99.5% purity).

Mechanical Characteristics	Value
Flexural strength	344 M Pa
Hardness	1000 kg/mm^2
Density	3.96 g/cm^3
Bulk modulus	170 G Pa
Modulus of elasticity	310 G Pa
Poisson's ratio	0.22
compression strength	2200 M Pa
Shear Modulus	125 G Pa
Fracture toughness	3.51 M Pa. M$^{1/2}$

The way alumina is treated has the potential to change its porosity. In the manufacturing of alumina, there are two basic chemical methods: The traditional process for making ceramic powder, which involves powder extraction, forming, and densification. The ceramics created using this method are extremely compact, with a porosity of less than 1%. The second approach is the sol-gel method, which is mostly used to produce porous Al_2O_3 for coatings applications with capable of 40% porosity [7,8]. The ecological impacts of Al_2O_3 based ceramics are usually minor, although this is not the case for processing processes. A usual ceramic powder procedure has a greater ecological impacts because of forming practice, which uses numerous binders, solvents, as well as other hazardous substances. In support of the sol/gel, physically powerful acids, binders, solvents, in addition to plasticizers were utilized [9]. Compounds that are organic conditional on the firing environment, various quantities of plasticizers and binders could be emitted as a byproduct of combustion, with serious environmental consequences [10].

Composites using Al_2O_3 matrix

The Al_2O_3 matrix composites are made up of Al_2O_3 that accounts for 82% from overall product weight. Zirconium oxide ZrO_2 nanoparticles, also known as zirconia nanoparticles, are additional to the Al_2O_3 matrix, accounting for 20% from total amount of volume. It is stabilised in tetragonal phase because they have good mechanical properties. The composites are reinforced in a variety of ways:

- In situ formation of elongated Strontium oxide SrO or Strontia crystals in Al_2O_3 matrix, as well as deflecting any subcritical cracks.
- Introducing tiny, distributed in a consistent manner Zirconium dioxide (ZrO_2) particles to Al_2O_3 matrix and afterwards establishing a conversion toughening.
- Using Chromium dioxide Cr_2O to create a solid alumina solution with greater durability.

The US Food and Drug Administration had been approved Al_2O_3 matrix composites used for as a code for Extra-High Molecular Weight Polyethylene in Implant Ball Heads. The initial quantifiable trials had been conducted in 2001, and in view of the fact that then, over 65000 ball heads had been implanted around the human race [11,12].

Al_2O_3 biomaterial applications

Alumina is not active *in vivo* and is resistant to corrosion. This causes a restricted tissue reaction that lasts several years. Because it is bioresorbable, the body recognizes and attempts to identify it as a contaminant by forming a fibrous capsule across the implant. Furthermore, when an aluminum product is placed, biomolecules and proteins quickly adsorb on the substrate, concealing the implant from the skin's immune reaction. In practice, the surface between tissues and alumina can be adjusted to avoid the configuration of fibrous sheathing across implants. Even though Al_2O_3 is biocompatible, implanted Al_2O_3 particles may cause a severe foreign-body reaction [13,14].

Mira [14] discussed how Alumina-ceramic alloys can be used in biomedical applications. Mira divided alumina ceramic into biodegradable, bioinert, and bioactive categories based on the body's response. Elisabet [15] has evaluated, analyzed, and described the usage of porous alumina. Biocompatibility, surface morphology, in-depth Nano structuring, surface processing, including coatings are all part of this investigation.

A review of the various applications of alumina in several biomedical domains, including dental applications, joint replacement, and bone spacers, was presented in the current research.

Nanoporous alumina

Using a diluted solution of either oxalic acid ($C_2H_2O_4$) or sulfuric acid (H_2SO_4) with anodizing voltages ranging from eight to 100 volt, planar and cylindrical Nano-porous alumina sheets with diameters ranging from five to 130nm can be produced [16]. The size of the pores is settled on with the width of the resulting Al_2O_3 surface, which preserve range from nanometres -100 of microns [17]. A two-steps anodization procedure are employed in the direction of obtaining great nanopore homogeneity. The Al_2O_3 surface is primary anodized in H_2SO_4 otherwise $C_2H_2O_4$. Anodization is ceased subsequent to absorbing an only some microns of Al_2O_3, and the transparent Al_2O_3 coating is removed throughout etching. An etchant, which is a mix of phosphoric acid (H_3PO_4), degrades Al_2O_3 even faster than aluminium, which is very selective. The leftover Al_2O_3 is dimpled, furthermore the dimples acting at the same time as standard seed surface from which an identical porosity layer can be created in second action of anodization. In this step, the precise size in addition to shape of the pore are estimated by adjusting the anodizing voltage [17,18]. With anodization voltage, the nanopore diameter grows at a rate of around 1.28 nm per volt. Fixed anodizing voltages produce straight pores, whereas stage process anodizing voltage adjustments can be employed to create decreasing diameter branch channels, enabling the creation of treelike nanoscale configuration. Nanoporous materials could serve as osseointegration enhancers on orthopaedic implants otherwise even as protein separation membranes [19,20].

Joint replacements made of alumina

It was initially found in the seventeenth century that it was feasible to use the characteristics of Al_2O_3 ceramics to enhance the applications of orthopedic implants. Alumina has been widely utilized for worn surfaces inside joint replacement prostheses since then, owing to their exceptional wear resistance. Al_2O_3 is commonly accustomed to make femoral heads intended for hip replacement in addition to wear plates for knee replacement implants.

So far, almost three million Al_2O_3 femoral heads have been implanted. Figures 1 and 2 depict full hip furthermore knee replacement implants, respectively. For hip replacement, an Al2O3 femoral head designed for the opposing articulating layer is combined with plastic femoral tip as well as an ace tabular cup made of EHMWPE or Al_2O_3. A success of such a joint substitute is determined by two factors [21]:

- The materials' wear and frictional properties.
- The quality of the implant's natural tissue anchoring.

Alumina wear levels on EHMWPE are roughly twenty times lesser than on UHMWPE for Iron, resulting in decreased debris output, according to research [22]. Wear debris causes complex and challenging diseases like osteolysis, which can lead to implant failure in the long run. A pair of Al_2O_3-Al_2O_3 ceramic bearings is preferred to Al_2O_3-EHMWPE otherwise metal bearings, consequential in good wear resistance in addition to reducing inflammatory responses to polyethylene [23]. Ceramic debris made of EHMWPE, on the other hand, has been found to be less harmful in tests. Alumina head fracture rates range from Zero percentage for ceramics made past 1990 to 13.4% for ceramics made before 1990. Prior to 1994, elevated fracturing levels of Al_2O_3 heads had been triggered when low-density Al_2O_3 with a very rough microstructure had been used [24,25].

Eventually, material scientists have been improved Al_2O_3 processing procedures, consequential in higher mechanical strength. A present generation is Al_2O_3-pressed, laser-labeled, and evidence-checked. This substance has been on the market since 1994. Femoral head fractures account for 0.004% of all fractures. Within whole knee replacements, Al_2O_3 is being used for parts that approach into contact with bone, while the blend of Al_2O_3 and EHMWPE is used within slipping regions. Polyethylene contamination in these devices causes significantly more serious problems than it does in hip implants [24,26].

Al_2O_3 isn’t the best material designed for orthopaedic applications. Al_2O_3 has a Young's modulus of 370-410 G Pa. This is higher than cancellous (0.055-0.55 G Pa) and cortical (06-26 G Pa) bone. Young's module is frequently based on a person's age as well as the position of bone tissue in the body. Consequently, the mechanical properties of Al_2O_3 in addition to bone are not compatible. The Al_2O_3 implant will protect the bone from whichever mechanical stress; furthermore, the implant will carry a full weight. These mechanical supports might cause stress concentration on the bone, causing it to resorb and deteriorate, ultimately leading to implant failure [27].

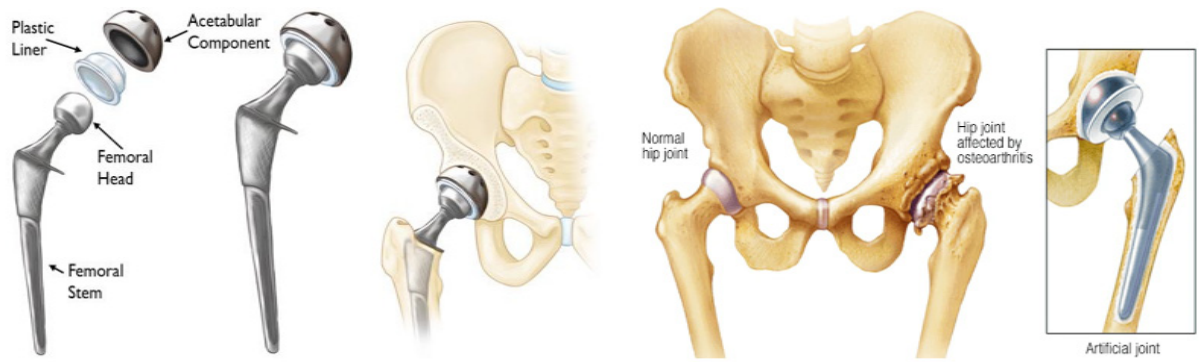

Figure 1: Replacement of the whole hip joint [28].

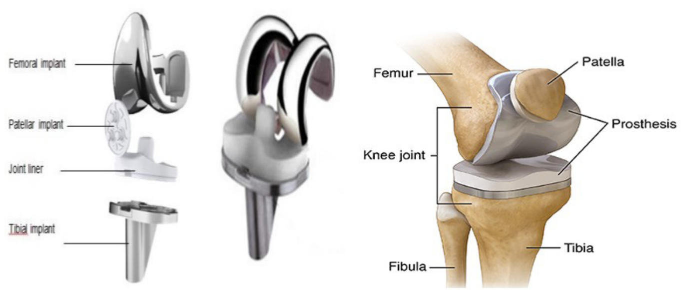

Figure 2: Knee replacement procedure [29].

Alumina applications in bone spacers

Bone spacers made of Al_2O_3 with a porosity of more than 30% could be utilized to replace missing bone components caused by traumatic injury or malignancy. As shown in Figure 3, metal pins are used to secure bone spacers to tissues. The dynamic elastic shape of the implant encourages bone cells to permeate it, eventually generating a new tissue structure. In most cases, the pore width is larger than 100 µm [30]. This could not only permit the bone to expand, but it could as well aid in the vascularisation of the bone [31].

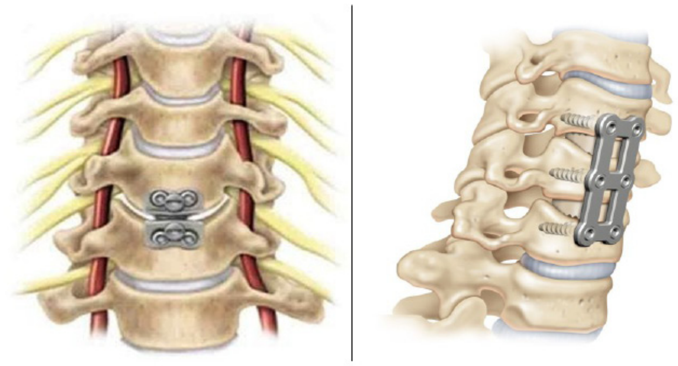

Figure 3: Replacement of the cervical spine [32].

Dental applications of alumina

As shown in Figure 4, high-density Al_2O_3 was employed for teeth replacement in dental applications. Single crystal Al_2O_3 is utilised intended for dental implants because polycrystalline Al_2O_3 be able to fracture during insertion into the root of the tooth. Single crystal Al_2O_3 has bending strength of 12500 kg/cm^2, which is higher than polycrystalline 3400 kg/cm^2. A cylindrical single crystal alumina core is often utilised in implants, with polycrystalline alumina fused all around it. There are some disadvantages to using alumina dental implants. They feature a modular implant system that allows for a lot of customization. As a result, alumina implants are becoming more acceptable, and dental porcelain replacements are becoming more popular [33,34].

Figure 4: Dental implants made of alumina [35].

Conclusion

In vivo, alumina is a highly inert substance that is also corrosion-resistant. Alumina produces little inflammation in the body and can be used for a long time. Although some implants are single crystals, polycrystalline alumina makes up the majority of the material. It is widely used due to its high strength, great tear resistance, biocompatibility, as well as high tensile strength. Furthermore, alumina provides the best tribological characteristics for articulating surfaces in orthopaedic implants. Applicants are concerned about high elasticity modulus, low toughness, cyclic failure, homogeneous crack growth, as well as tensile strength sensitivity. Nevertheless. Recently, it was discovered that investing in alumina matrix ceramics could improve the implant lifespan by 15 years. Alumina's use in dental, orthopaedic, and maxillo-facial procedures is predicted to grow rapidly in the near future.

Alumina's other applications

Alumina has been used as a joint spacer for bones or implants in otolaryngology and maxillofacial surgery. Al_2O_3 implants have in addition been employed in neurosurgical procedures for instance Cranioplasty as shown in Figure 5. Alumina was used in Keratoprosthesis as shown in Figure 6. In addition, porous alumina has been utilised to control the long-term dispersion of vaccines, medicines, and hormones.

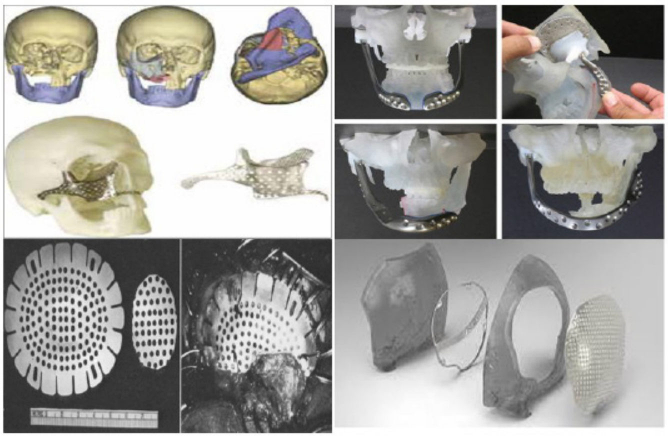

Figure 5: In otolaryngology and maxillofacial surgery, alumina has been employed [36].

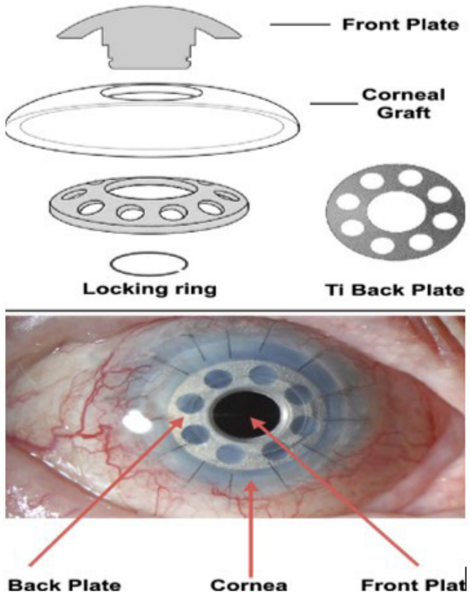

Figure 6: In Keratoprosthesis, alumina has been employed [37].

Declarations

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References

1. Ruys A. Dental, tissue scaffold, and other specialized biomedical applications of alumina. In: Alumina Ceramics. 2019; 123-137.
2. Sedel L, Nizard R, Meunier A. Orthopedic biomaterials. Bull Acad Natl Med. Epub ahead of print. 1995; 179: 198.
3. Rahmati M, Mozafari M. Biocompatibility of alumina-based biomaterials–A review. Journal of Cellular Physiology. 2019; 234: 3321-3335.
4. Lin B, Heng L, Fang B, Yin H, Ni J, et al. Ammonia Synthesis Activity of Alumina-Supported Ruthenium Catalyst Enhanced by Alumina Phase Transformation. ACS Catal. 2019; 9: 1635-1644.
5. Zahra AT. Technological Advancements to Reduce the Influence of Absorption and Scattering on the Optical Imaging. Bangladesh Med Res Counc Bull. 2020; 46: 64-65.
6. AL-Timimi Z. Improvement of antibiotics absorption and regulation of tissue oxygenation through blood laser irradiation. Heliyon. 2021; 7: e06863.
7. Levin I, Brandon D. Metastable alumina polymorphs: Crystal structures and transition sequences. J Am Ceram Soc. 1998; 81: 1995-2012.
8. Levin I, Brandon D. ChemInform Abstract: Metastable Alumina Polymorphs: Crystal Structures and Transition Sequences. ChemInform. 2010; 29.
9. Al-Timimi Z. Cancer treatment based on the selective accumulation of a photosensitiser and laser light irradiation: A review. Bangladesh Medical Research Council Bulletin. 2020; 46: 150-153.
10. Zahra A-T. A Comparative Study of Determination the Spectral Characteristics of Serum Total Protein among Laser System and Spectrophotometric: Advantage and Limitation of Suggested Methods. Curr Anal Chem. 2019; 15: 583-590.
11. Dohan Ehrenfest DM, Corso M Del, Kang B-S, et al. Identification card and codification of the chemical and morphological characteristics of 62 dental implant surfaces. Part 1: description of the Implant Surface Identification Standard (ISIS) codification system. poseido. 2014; 2: 7-22.
12. Montazerian M, Zanotto ED. Bioactive and inert dental glass-ceramics. Journal of Biomedical Materials Research - Part A. 2017; 105: 619-639.
13. Lee SS, Huber S, Ferguson SJ. Comprehensive in vitro comparison of cellular and osteogenic response to alternative biomaterials for spinal implants. Mater Sci Eng C. 2021; 127: 112251.
14. Mohanty M. Medical applications of alumina ceramics. Trans Indian Ceram Soc. 1995; 54: 200-204.
15. Xifre-Perez E, Ferre-Borull J, Pallares J, Marsal LF. Mesoporous alumina as a biomaterial for biomedical applications. Open Mater Sci; 2. Epub ahead of print. 2015; 2: 4.
16. Coluzzi DJ, Al Timimi Z, Saleem M. Digitization and Dental Lasers. In: Digitization in Dentistry. 2021; 141-167.
17. A A-TZ. Exploration of Additional Mechanical Phenomena of Laser-Tissue Interaction Contributes to the Damage and Elimination of the Small Blood Vessels. Int J Sci Eng Res. 2014; 5: 672-675.
18. Niazi FK, Umer MA, Ahmed A, Hafeez MA, Khan Z, et al. Nanoporous alumina membranes for sugar industry: An investigation of sintering parameters influence onultrafiltration performance. Sustain. Epub ahead of print. 2021; 13: su13147593.
19. Zaraska L, Kurowska E, Sulka GD, Jaskula M. Porous alumina membranes with branched nanopores as templates for fabrication of Y-shaped nanowire arrays. J Solid State Electrochem. 2012; 16: 3611-3619.
20. Fang J, Levchenko I, Van Der Laan T, Kumar S, Ostrikov K. Multipurpose nanoporous alumina-carbon nanowall bi-dimensional nano-hybrid platform via catalyzed and catalyst-free plasma CVD. Carbon. 2014; 78: 627-632.
21. Chen W, Yuan JH, Xia XH. Characterization and manipulation of the electroosmotic flow in porous anodic alumina membranes. Anal Chem. 2005; 77: 8102-8108.
22. Timimi ZA. The Performance of the Cold Laser Therapy (GaAlAs-980nm). Pakistan J Med Heal Sci. 2021; 15: 3096-3102.
23. Al-Timimi ZJMA. Impact of Low - Energy Fluencies Laser Irradiation at 532 nm on Neutrophils and Lymphocytes Blood Counting. Iraqi Laser Sci J. 2019; 1: 21-28.
24. Barakat DA, Al-Abbas G, Al-Timimi ZJMA. Utilization of diode laser therapy with wavelength 904nm during pregnancy: A preliminary study. Iraqi Laser Sci J (ILSJ). 2019; 1: 2019.
25. Bal BS, Garino J, Ries M, Garino JP. Ceramic Materials in Total Joint Arthroplasty. Semin Arthroplast JSES. 2006; 17: 94-101.
26. Katz JN. Surgical management of osteoarthritis: options and outcomes. Osteoarthr Cartil. 2012; 20: S4.
27. BS Bal, J Garino, M Ries, MN Rahaman. A review of ceramic bearing materials in total joint arthroplasty. HIP Int. 2007; 17: 21-30.
28. AL-Timimi Z, Mustafa F. Recognizing the effectiveness of the diode laser 850nm on stimulate the proliferation and viability of mice mesenchymal stem cells derived from bone marrow and adipose tissue. Iraqi J Vet Sci. 2019; 32: 285-290.
29. Patton RS, Runner RP, Lyons RJ, Bradbury T. Clinical Outcomes of Patients with Lateral Femoral Cutaneous Nerve Injury after Direct Anterior Total Hip Arthroplasty. J Arthroplasty. 2018; 33: 2919-2926.e1.
30. Vaidya SV, Jogani AD, Pachore JA, Armstrong R, Vaidya CS. India Joining the World of Hip and Knee Registries: Present Status—A Leap Forward. Indian J Orthop. 2021; 55: 46-55.
31. Diam WA, Zahra A-T. Characterization and fabrication of Nd: YVO4 disc laser system. In: AIP Conference Proceedings. American Institute of Physics Inc. 20009.
32. Al-Timimi J. Impact of laser (Nd: YVO4 Crystals, 532nm) radiation on white blood cells. Iraqi Laser Sci J. 2019; 1: 1-6.
33. Alvin MD, Mroz TE. The Mobi-C cervical disc for one-level and two-level cervical disc replacement: A review of the literature. Medical Devices: Evidence and Research. 2014; 7: 397-403.
34. Catauro M, Bollino F. Advanced Glass-Ceramic Materials for Biomedical Applications. J Bone Reports Recomm. Epub ahead of print. 2017; 3: 35.
35. Piconi C, Sprio S. Oxide bioceramic composites in orthopedics and dentistry. Journal of Composites Science. Epub ahead of print. 2021; 5: 206.
36. Huang MF, Alfi D, Alfi J, Huang AT. The Use of Patient-Specific Implants in Oral and Maxillofacial Surgery. Oral and Maxillofacial Surgery Clinics of North America. 2019; 31: 593-600.

37. Zhou C, Lei F, Chodosh J, Paschalis EI. The role of titanium surface microtopography on adhesion, proliferation, transformation, and matrix deposition of corneal cells. Investig Ophthalmol Vis Sci. 2016; 57: 1927-1938.