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Bone Bonding of Hafnium – A Literature Review

Vaishnavi Rajaraman[1], Deepak Nallaswamy[2], Dhanraj Ganapathy[3] and Thiyaneswaran Nesappan[4]

[1]Post-Graduate, Department of Prosthodontics and Implantology, Saveetha Dental College and Hospital, Saveetha Institute Of Medical and Technical Sciences, Saveetha University, Chennai, India
[2]Professor, Director of Academics, Saveetha Dental College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India
[3]Professor and Head, Department of Prosthodontics and Implantology, Saveetha Dental College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India
[4]Professor, Department of Prosthodontics and Implantology, Saveetha Dental College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India

ABSTRACT

Numerous biomaterials have been constantly researched upon for dental implants. We wanted to evaluate alternative elements that may have the potential to offer equivalent or superior osseointegration. One such element of interest is Hafnium. In the periodic table by IUPAC, tantalum belongs to period 6 (d block) of periodic table. Hafnium belongs to the same period and block as tantalum, in the periodic table. Various in vitro studies were conducted on hafnium metal. Studies have reported that hafnium has a similar response in soft and hard tissues in two different animal species (rat and rabbit), which suggests that hafnium might be an interesting material for biomedical applications. This review aims at analysing the existing literature on hafnium as potential implant biomaterial.

KEY WORDS: HAFNIUM, OSSEOINTEGRATION, COATING, IMPLANT BIOMATERIAL, BIOCOMPATIBILITY, TITANIUM.

INTRODUCTION

For a successful design of a dental implant, it is of utmost importance to have the knowledge about material science together with the biomedical considerations. The prime requirements for dental implants are appropriate mixture of mechanical properties and biocompatible properties. An ideal implant material should have biocompatibility (Smith, 1991; '13 Implant Material Properties', 2015; Duraisamy et al., 2019), corrosion resistance (Solar, no date),(Greene, no date; Syrett and Davis, no date), elastic modulus (Song et al., 2011), and good bone anchorage (Sakka and Coulthard, 2009; Gabet et al., 2010).

One of the most commonly used materials for this purpose is titanium and its alloys (Adya et al., 2005; Chaturvedi, 2009). In various studies conducted till date, Tantalum has revealed superior properties fulfilling criteria required for an implant which include excellent chemical stability, body fluid resistance, biological inertia and remarkable osteoconductivity (Committee and F04 Committee, no date; Balla, Bodhak, et al., 2010). Although tantalum is shown to be promising in bone defect repair (Tang et al., 2013; Mrosek et al., 2016; Wang et al., 2018), its elastic modulus (Leigh, 2011; Parsons, 2014; Constable, 2019)is much higher than that of human bone tissue (Arciniegas et al., 2007; Lu et al., 2015) and prone to stress shielding effect (Saha, Inturi and Barnard, 1996; Korabi, Shemtov-Yona and Rittel, 2017).

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**Corresponding Author: drvaish.sav@gmail.com*
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In the periodic table by IUPAC , tantalum belongs to period 6 (d block) of periodic table (Leigh, 2011; Parsons, 2014; Constable, 2019; Scerri, 2019). Hafnium belongs to the same period and block as tantalum, in the periodic table (Leigh, 2011; Parsons, 2014; Constable, 2019). Previously our department has published extensive research on various aspects of prosthetic dentistry ('Evaluation of Corrosive Behavior of Four Nickel–chromium Alloys in Artificial Saliva by Cyclic Polarization Test:An in vitro Study', 2017; Ganapathy, Kannan and Venugopalan, 2017; Jain, 2017a, 2017b; Ranganathan, Ganapathy and Jain, 2017; Ariga et al., 2018; Gupta, Ariga and Deogade, 2018; Anbu et al., 2019; Ashok and Ganapathy, 2019; Duraisamy et al., 2019; Varghese, Ramesh and Veeraiyan, 2019), this vast research experience has inspired us to research about This review aims at analysing the existing literature on hafnium as potential implant biomaterial.

Review of Literature

History of Dental Implants: Tracing back, the record of the first use of implants as a biomaterial to perform immediate replacement of a lost tooth was attempted by the use of volcanic glass which was shaped like a tooth itself in the era of the Mayans (Metz, 1992; Gehrke, 1997; Crabb, 2006). The first metal used in implantology was Gold,in 1809, by Maggiolo, an Italian dentist (Maggiolo, 1809). He also followed the same immediate implantation method after extraction whose root shape matched the tooth socket like the Mayans. Slowly, other metals came into use like platinum, iridium, lead, rubber and porcelain (Brunski, 1988; Meffert, Langer and Fritz, 1992; Duraccio, Mussano and Faga, 2015; García-Gareta et al., 2017; V. Rajaraman, Dhanraj and Jain, 2018). In 1934, Hans Abel used ferrous alloys as implants (Steinemann and Perren, 1977; Miyazaki and Others, 1998).

The first implant that resembled the modern dental implant configuration was designed by Strock in 1983 (Linkow and Dorfman, 1991; Burch, 1997). It was manufactured from cobalt-molybdenum alloy. Currently, for the past few decades, titanium and its alloys are the abundantly used metal in dental implantology (Patil, 2015); (Saini, 2015) . Due to its inertness, low elastic modulus (Graft and Rostoker, no date; Baumgarten, 2018), biocompatibility and resistance to change in oral fluids, pure titanium is mostly preferred as a dental implant biomaterial (McCracken, 1999; Elias et al., 2008; Niinomi and Nakai, 2011; Saini, 2015).

Non-metal materials started to be produced as dental implants, in order to improve the aesthetic aspects (Campbell, 1999). The first ever ceramic material used in implantology was aluminium oxide, owing to its good osseointegration properties (Jahnke and Plester, 1981; Albrektsson et al., 1983). The implant systems manufactured with aluminium oxide were used for immediate implantation in single tooth loss cases, especially in the areas of relatively weak forces like anteriors (Albrektsson et al., 1986; Oshida et al., 2010). The success of these implants was between 87% and 92.5%, in the follow-up examinations after 10 years (Albrektsson et al., 1983, 1986). Due to their inadequate mechanical strength, when subjected to occlusal forces, aluminium-oxide implants were discontinued (Roland-Taylor, no date). Though these implants were used in clinical practice earlier, another superior substitute ceramic material was introduced later ,the zirconium (Correia et al., 2013; Patil, 2015; Focsaneanu et al., 2017; Kaur, Sherrill and Duan, 2019; Kim and Lee, 2020). However, failures still exist in these materials in spite of the survival rates of these biomaterials (Rajaraman et al., 2018)

Methods To Determine Osseointegration: The implant stability can be measured by invasive or non-invasive methods namely, radiography (Nogueira et al., 2006; Atsumi, Park and Wang, 2007); (Rajaraman et al., no date; McFarland, 1954), cutting torque analysis (Friberg et al., 1995; Atsumi, Park and Wang, 2007), impact hammer method (Teerlinck et al., 1991; Wijaya et al., 2004), reverse torque test (Sullivan et al., 1996; Simeone, Rios and Simonpietri, 2016; Nallaswamy, 2017), insertion torque analysis (Tricio et al., 1995; Lages, Oliveira and Costa, 2018), pulse oscillation waveform (Meredith, 1998; Atsumi, Park and Wang, 2007) , percussion test (Dario, Cucchiaro and Deluzio, 2002; Vaidya et al., 2017) and resonance frequency analysis (Ersanli et al., 2005; Atsumi, Park and Wang, 2007; Deng et al., 2008). Radiograph is a noninvasive method but only when demineralization exceeds 40%, it detects the density change (Halse et al., 1994; Yang and Dutra, 2005; White and Pharoah, 2018).

The removal torque analysis is an invasive method that involves the disturbance of bone implant contact which was proposed by Roberts et al 1984 (Favero, Pisoni and Paganelli, 2007; Rittel, Dorogoy and Shemtov-Yona, 2018). The disadvantage is that it's a destructive method that can irreversibly harm the bone surrounding implant. Percussion test, pulsed oscillation waveform and implant hammer method are similar to principles used in periodontics, which are based on vibration, mechanical and acoustic signals (Meredith, 1998; Dario, Cucchiaro and Deluzio, 2002; Jung et al., 2003; Atsumi, Park and Wang, 2007; VanSchoiack et al., 2013; Nallaswamy, 2017). The best method uses resonance frequency analysis (RFA) that measures the implant stability quotient (ISQ), with values greater than 65 showing good osseointegration (Ersanli et al., 2005; Deng et al., 2008; Abrahamsson, Linder and Lang, 2009; Bafijari et al., 2019; Charatchaiwanna et al., 2019; Kastala and Ramoji Rao, 2019).

Osseointegration – Why The Prime Focus: Osseointegration is influenced by the surface properties and the surface chemistry of dental implants (Taché et al., 2004; Sul et al., 2009; Sartoretto et al., 2015). The bone-implant interface is the site where biological reactions occur. Studies have reported that the surface features of the implant material promoted the osteoblast cell proliferation and thus accelerated the process of osseointegration (Anselme, 2000; Osathanon et al., 2011; Song et al., 2013). Another study researched the biomechanical property, biocompatibility and bioactivity of the Ti-Nb-Hf alloy, fabricated with a low Young's modulus as a dental implant biomaterial (Kim, Jeong and Choe, 2011; González et al., 2014). Some studies suggest that Ti-Nb-Hf implants have biological potential similar to cast pure titanium (cpTi), and they have remarkable osseointegration (Niinomi, 2003; Bai et al., 2016).

The biocompatibility of niobium, tantalum, hafnium and zirconium metals have been established with in vitro murine osteoblastic cell lines(Matsuno, 2001; Biesiekierski et al., 2012; Niinomi, Narushima and Nakai, 2015; Stenlund et al., 2015). To improve the biological behaviour of the titanium alloys, many modifications have been studied that include bioactive ions such as calcium(Ca), (Kizuki et al., 2010; Yamaguchi et al., 2010), zinc (Zn) (Yamaguchi et al., 2012) and strontium (Sr) (Yamaguchi et al., 2013; Cacciotti, 2017), that have enhanced the bone formation capacity (Gil et al., 2002; Zhang et al., 2013; Su et al., 2017; Vaishnavi Rajaraman, Dhanraj and Jain, 2018).

Coating Process: Various coating techniques exist in the field of implant manufacturing that are constantly being researched upon to enhance the regeneration of bone in the titanium bone implant interface (Pazo, Saiz and Tomsia, 1998; Gineste et al., 1999; Darimont et al., 2002; Nguyen et al., 2004; Bedi et al., 2009; Wen, 2015). These include physicochemical and biochemical coating techniques that are recently investigated (Lacefield, 1998; Roy, Bandyopadhyay and Bose, 2011; Xuereb, Camilleri and Attard, 2015). The purpose of these coatings over titanium surfaces is primarily to create a smooth transition from bony hard tissue to metallic implant surface (Keller et al., 1994; Wiskott and Belser, 1999; Bedzinski et al., 2010; Subramani, 2010; Bosco et al., 2012). The coatings should intend to form a physiological connection between the titanium surface and surrounding bone tissue and also replicate the organic and inorganic constituents of living bone tissue. In this way, the coated titanium implants aid to enhance strong integration by initiation of bone formation (Oates, 2001; Miron et al., 2010; Bosco et al., 2012; Kohal et al., 2013).

Many coating techniques have been investigated and implemented such as dry deposition, plasma spraying (Yang et al., 2000; Heimann and Lehmann, 2015; Xuereb, Camilleri and Attard, 2015); (Li et al., 2017), resonance frequency magnetron sputtering (Yokota et al., 2014; Das and Shukla, 2020), pulsed laser deposition (Garcia-Sanz et al., 1997; Czél, Teghil and Janovszky, 2003), ion beam assisted deposition (Ohtsuka et al., 1994; Yoshinari, Klinge and Dérand, 1996), biomimetic deposition (Rigo et al., 2004; Zhang, Leng and Xin, 2005; Fuming, Guoli and Xiaoxiang, 2008; Kim et al., 2011; Stefanic et al., 2012), sol-gel deposition (Lacefield, 1998), electrophoretic deposition and electrospray deposition (Yang et al., 2000; Heimann and Lehmann, 2015; Xuereb, Camilleri and Attard, 2015). The concept of type of coatings has drifted from a passive protecting layer in the 1980s to bioactive layers (Graber, 1982; Manero et al., 2002; Nogueras-Bayona et al., 2004). In recent times, plenty of coating techniques are being studied and this will be discussed in detail in our next section.

Latest Research on Coatings: The bone implant surfaces are increasingly added with biomolecules to fasten the process of healing of bone. To obtain the optimal therapeutic efficacy, these biomolecules need to be immobilized from the surface of implants (Gao et al., 2009; Bosco et al., 2012). For this purpose, a wide variety of biomolecules such as growth factors, bioactive proteins, enzymes, and non-viral genes (DNAs, RNAs) are currently being evaluated pre-clinically (Tonetti, Hämmerle and European Workshop on Periodontology Group C, 2008; Shimono et al., 2010; Quesada-García et al., 2012; Arya et al., 2019; Mohamed, El-Mohandes and El-Feky, 2019).

The Shift Towards Newer Biomaterial Coatings: The reason for the modification of dental implant surfaces with biomaterial coatings is to enhance the osseointegration and decrease the time required for healing (Taché et al., 2004; Javed et al., 2014; Wang et al., 2015; Wen, 2015)(Garcia-Sanz et al., 1997; Darimont et al., 2002; Rigo et al., 2004; Bosco et al., 2012); (Taché et al., 2004; Javed et al., 2014; Wang et al., 2015; Wen, 2015). The portion of the dental implant that comes in immediate contact with the surrounding living tissue is its surface. Various surface coatings have been tried, to modify the texture and bioactive properties for the improvement of osseointegration (Balla, Banerjee, et al., 2010; Stefanic et al., 2012; Yang et al., 2012; Tang et al., 2013). The principle mechanism of these types of coatings is on the lines of increase in the functional surface area of the implant available at the bone-implant interface for osseointegration which would consequently lead to efficient distribution of stress (Sykaras et al., 2000; Gardon and Guilemany, 2014; Sartoretto et al., 2015).
The implant modifications can be achieved either by additive or subtractive methods.

The additive methods include the process in which other biomaterials are coated or impregnated, by adding onto the surface (Petrovic et al., 2012; Wang et al., 2016). Coatings like plasma sprayed titanium exhibit high roughness compared to machined surfaces (Cooper et al., 1999; Xie et al., 2005; Endres et al., 2008). Hydroxyapatite (HA) coatings decrease the healing period (Garcia-Sanz et al., 1997; Darimont et al., 2002; Rigo et al., 2004; Bosco et al., 2012). Subtractive techniques involve the procedure of removal of the layer of the surface of core material (Anil et al., 2011; Parekh, Shetty and Tabassum, 2012; Jemat et al., 2015; Mistry et al., 2016). This could be by various means like mechanical methods by shaping/removing, grinding, machining, or grit blasting via physical force (Wennerberg, 1996; Kim et al., 2014; Shemtov-Yona, Rittel and Dorogoy, 2014).

The chemical methods are by using acids or alkali solutions to change the surface roughness and to induce the wettability of the surface (Li et al., 2002; Zareidoost et al., 2012; Al-Radha and Al-Radha, 2016). Another method is the physical treatment such as plasma or thermal spray

(Wang, Khor and Cheang, 1998; Lavos-Valereto et al., 2001; Roy, Bandyopadhyay and Bose, 2011; Robotti and Zappini, 2019). Additionally, ion implantation (De Maeztu, Alava and Gay-Escoda, 2003; De Maeztu et al., 2007; Su et al., 2017), laser treatment (Lacefield, 1998; Hindy, Farahmand and Tabatabaei, 2017) and sputtering (Lacefield, 1998; Rigo et al., 2004; Yokota et al., 2014) are also sort for coating surfaces. Of the methods described, additive methods have been established as more effective for surface characterization. In our study, we employed a coating technique to achieve standardized results.

The behavior of modified surface on cells culture studies has revealed that an acid etched zirconia implant surface shows a significant improvement in cell proliferation (Langhoff et al., 2008; Kohal et al., 2013; Noro et al., 2013; Schünemann et al., 2019). Commercially pure titanium surface was blasted followed by two-step chemical treatment (acid-alkali) resulting in optimized surface topography (Parsikia, Amini and Asgari, 2012; Jemat et al., 2015; Moon et al., 2017). The cell bioactivity was improved and expected to have good osseointegration at an early stage. Titanium implant surfaces coated with bioactive glass were osseointegrated into host bone without any intervening of connective tissue capsue with high removal torque than uncoated titanium surfaces (Kim and Kwon, 1997; Bloyer et al., 1999; Moritz et al., 2004; Mistry et al., 2011) . Hydroxyapatite coatings integrate faster and they provide a combination of mechanical properties of the titanium and bioactivity of hydroxyapatite (Lacefield, 1998; Rigo et al., 2004; Bosco et al., 2012).

Calcium phosphate crystals within TiO2 layer are impregnated to the surface, in different thicknesses on the surface of titanium core material to enhance the osseointegration (Feng et al., 1999; Mendes, Moineddin and Davies, 2007; Reiner, Klinger and Gotman, 2011; Bosco et al., 2012). Nitride coatings by a process called plasma nitriding improves the mechanical strength, surface hardness and the corrosion resistance of the dental implant (Shi et al., 2012; Rizzi et al., 2014; Seo et al., 2017; Ozmeric et al., 2019). Fluoride treatment of implant surface causes formation of soluble TiF4 that accelerates the osseointegration (Le Guéhennec et al., 2007; Surender et al., 2011; Dahiya, Shukla and Gupta, 2014; Barfeie, Wilson and Rees, 2015) . Recently, bioactive drugs including bisphosphonate , simvastatin and antibacterial coatings like gentamicin and tetracycline are being researched upon (Chudzik et al., 2006; Le Guéhennec et al., 2007; Wennerberg et al., 2013). Thus, the surface treatment is used not only to maintain the existing properties of the implants but also to enhance several behaviours as required by dental applications particularly in improving the healing process.

New Metal - Hafnium: Hafnium also called ‘Hafnia’ was first discovered by Dirck Coster and Georges de Hevesy in Copenhagen, 1923 (Coster and Hevesy, 1923). The word is Latin for Copenhagen. It is found in nature along with Zirconium as a mineral ore called zircon (‘PHYSICAL PROPERTIES OF ZIRCONIUM AND HAFNIUM’, 1970; Mukherji, 2013). The main mineral where it is found is zircon, with a ratio of Hafnium/Zirconium of about 2.5% (Predel, no date). The ideology behind introduction of this material is its position in the periodic table of elements. The metal Hafnium belongs to the same group (Group 4) as titanium and zirconium and is in the period (Period 5) as tantalum of the periodic table of elements. Considering the common properties of a group in periodic table, hafnium seems to possess ideal properties for dental implants.

Hafnium is a passive metal , with no reactiveness in body fluids. It has various mechanical advantageous properties like strength, high ductility, chemical inertness, resistance to corrosion and mechanical damage (‘PHYSICAL PROPERTIES OF ZIRCONIUM AND HAFNIUM’, 1970). Owing to its good biocompatibility and osteogenic capability, hafnium has been suggested as a potential biomaterial for orthopaedic applications. Hafnium has also been used as an alloying element in various metals like iron, titanium, niobium etc. It also finds use as a control material for nuclear reactors and as an alloying element in some super alloys used in aircrafts engines (Risovany, Klochkov and Ponomarenko, 2001); (Ruane and Storm, 1959).

CONCLUSION

In attempt to replace a missing tooth, apt selection of the implant biomaterial is a significant factor for long term success of implants. The implants should be selected in such a manner so as to minimise the negative biologic response while maintaining acceptable function. Research has shown promising results for hafnium as a biocompatible material. These studies were mostly in vitro and animal studies. Although this remains proven, little evidence is available on its osseointegration properties of hafnium and its behaviour in the intraoral environment. Thus, further studies of hafnium coating under biological conditions are needed in order to determine the suitability of this material, as a surface coating for biomedical applications.

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