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Titanium Nitride Coated Implant Abutments: From Technical Aspects And Soft tissue Biocompatibility to Clinical Applications. A Literature Review

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Abstract

Purpose: To review the most up to date scientific evidence concerning the technical implications, soft tissue biocompatibility, and clinical applications derived from the use of titanium nitride hard thin film coatings on titanium alloy implant abutments.
Materials and Methods: A review was performed to answer the following focused question: "What is the clinical reliability of nitride coated titanium alloy abutments?". A MEDLINE search between 1980 and 2021 was performed for investigations pertaining to the clinical use of nitride coated titanium alloy implant abutments (TiN) in case reports, case series, and short- and long-term non/randomized controlled clinical trials. Literature analysis led to addition evaluation of research related to the technical and biological aspects, as well as the physicochemical characteristics of TiN hard thin film coatings and their impact on titanium abutment biocompatibility, mechanical properties, macroscopic surface topography, and optical properties. Therefore, preclinical data from biomechanical and in vitro investigations were also considered as inclusion criteria.
Results: The limited number of clinical investigations published made a systematic review and meta-analysis not possible, therefore a narrative review was conducted. TiN coatings have been applied to dental materials and instruments to improve their clinical longevity. Implant abutments are coated with titanium nitride to mask the titanium oxide surface and enhance its surface characteristics providing the TiN abutment surface with a low friction coefficient and a very high chemical inertness. TiN coating is suggested to reduce early bacterial colonization and biofilm formation and enhance fibroblast cell proliferation, attachment and adhesion when compared to Ti controls. Additionally, studies indicate that hard thin film coatings enhance the mechanical properties (hardness and wear resistance) of titanium alloy and appears as a yellow color when deposited on the titanium alloy substrate. To date, clinical investigations show that nitride coated titanium abutments provide promising short-term clinical outcomes.
Conclusions: Published research on nitride-coated abutments is still limited, however, the available biomedical research, mechanical engineering tests, in vitro investigations, and short-term clinical trials have, to date, reported promising mechanical, biological, and esthetic outcomes.

The use of titanium abutments has limitations especially in the esthetic zone due to peri-implant mucosa discoloration when a thin phenotype is present.[1,2] In these cases, monolithic zirconia abutments have been recommended.[3] However, in vitro studies showed that the fracture resistance of zirconia abutments is half of that reported for titanium abutments.[4] To overcome the mechanical limitations of one-piece zirconia abutments while maintaining their esthetic advantages, hybrid metal-zirconia abutments have been recommended,[5,6] although their fabrication requires additional laboratory steps. Therefore, research indicates that no abutment material is capable of providing the ideal esthetic and mechanical properties for all clinical scenarios.

Stock metal abutments have been used in implant dentistry for cement-retained prostheses. However, the relative inability to customize these abutment margins to the surrounding peri-implant mucosa may lead to the placement of excessively deep margins, incomplete cement removal, cement retention, and biologic complications, such as periimplantitis.[7,8] Computer-aided design and computer-aided manufacturing (CAD-CAM) technology allows the fabrication of titanium abutments with customized margin positions and emergence profiles.[9,10] While titanium biocompatibility has been sufficiently demonstrated,[11] titanium CAD-CAM abutments can be coated with titanium nitride hard thin film coating (TiN) in order to mask the titanium oxide layer, and improve the abutment surface characteristics while maintaining titanium biocompatibility. Preliminary reports indicate that TiN coating enhances fibroblast cell proliferation, attachment and differentiation, and also reduces bacterial adherence and biofilm formation. Therefore, these abutments are being considered as alternatives to traditional gold, titanium, high-strength polycrystalline ceramic abutments, and hybrid abutments, although scientific data is still limited. This review describes the most up to date evidence on TiN-coated custom abutments, focusing on their enhanced soft tissue biocompatibility, identifying their most relevant biomechanical and esthetic properties, and describing their most relevant clinical applications.

Materials and methods

A MEDLINE search was performed for English language publications between 1980 and 2021, pertaining to the clinical use of nitride coated titanium alloy implant abutments in case reports, case series, and short- and long-term non/randomized controlled clinical trials. The following keywords and terms were used: titanium, nitride, titanium nitride, implant abutments, coating, soft tissue, color, and biocompatibility. A preliminary screening analyzed all titles and abstracts obtained. Those which did not provided sufficient and/or pertinent information related to the objective of the present investigation were discarded. After careful review of titles and abstracts of the referenced publications, the full-texts of those considered to "possibly" add valuable information to the area of interest of the present review, were also obtained, printed, and reviewed. This protocol enabled broadening the scope of the review to include preclinical data from biomechanical investigations and animal studies.

For a coherent revision of the present research, data was organized in six main topics: titanium nitride as a coating material for medical and dental applications; biocompatibility; surface hardness and wear resistance; optical properties; limitations; and clinical applications of titanium nitride coated abutments.

Results

Titanium nitride as a coating material for medical and dental applications

Hard material coatings such as TiN have been used on cutting tools as well as on machine parts and decorative elements. In medicine, TiN has been used to coat orthopedic implants (hip and knee replacement prostheses) in order to reduce attrition coefficient, wear and corrosion, and increase surface hardness.[12–14]

Several coating technologies have been proposed for the deposition of thin ceramic coatings (TiN and ZrO_2) on titanium surfaces, such as physical vapor deposition (PVD), thermal application, chemical vapor deposition (CVD),[15] and Nd:YAG laser gas.[16,17] These techniques allow for the thin TiN coating to be formed by the reaction of pure titanium (as a substrate) and highly reactive monoatomic nitrogen gas in the vapor phase.[18,19] In an extensive review on the physical properties of TiN coatings, Al-Jabbari et al[15] reported the coating layers to have a mean thickness between 1 and 5 μm with ranges between 0.06 and 10 μm. Qualitatively, TiN coatings may be deposited as a monolithic (single) uniform layer or in a more complex multilayered structure.[15]

In dentistry, TiN coating was introduced in the 1980s.[20–22] Since then, TiN coatings have been applied to dental materials and instruments used in implant dentistry, orthodontics, endodontics, periodontics, and prosthodontics. More recently, dental implant abutments have been coated with TiN to couple the biomechanical properties of titanium with the requirements for esthetics in anterior implant cases.[23–25] In addition, TiN coatings changed the implant/abutment's surface chemical composition and mechanical properties thus reducing the interaction with biologic fluids and increasing the hardness and wear resistance of the metal substrate.[15,26–28] Reports have also shown TiN as having very high chemical inertness and low friction coefficient.[24,29]

Biocompatibility

Biocompatibility and cellular response to different abutment materials and surface modifications varies.[30,31] Titanium, a reactive metal, is always covered by a titanium dioxide layer of approximately 5 to 20 nm thickness.[9] Hard thin film coatings (TiN and ZrN) can mask the titanium oxide surface and modify the surface characteristics while keeping the material´s biocompatibility.[32] Indeed, several studies showed that fibroblast cell proliferation, attachment, and adhesion on TiN samples is similar[33–37] when compared to machined Ti controls. Other reports[38] showed that TiN coating deposited by Physical Vapor Deposition revealed an increase in fibroblast growth on zirconium nitride and titanium nitride when compared to polished titanium.

In addition, TiN coating is suggested to reduce early bacterial colonization and biofilm formation. Gröbner-Schreiber et al, in both in vitro[39] and in vivo[40] studies, showed significantly fewer adherent bacterial colonies on TiN and ZrN coated surfaces. These results were confirmed by Scarano et al[41] who showed a significant reduction of bacterial adhesion on TiN-coated titanium implants when compared to control, uncoated ones. Bacterial adhesion can be enhanced by surface roughness and generally, a maximum Ra value of 0.2 μm is suggested in order to minimize plaque formation and enhance a stable soft tissue seal around the abutment.[42–45] In this sense, TiN coating has been shown to be generally below this threshold, with documented Ra values of 0.159 $\pm$0.040 μm and 0.217 $\pm$0.025 μm when measured with confocal microscopy and white light interferometry, respectively.[46]

While the effect of TiN coating on clinical peri-implant bone loss has been shown to be similar to other implant

Figure 1 The gold color that characterizes TiN abutments is due to a natural phenomenon known as "light interference." Titanium nitride color characteristics, wavelength and purity, are very close to those of standard pure gold.

surfaces,[47] TiN coatings have been suggested to reduce bacterial adherence and biofilm formation without compromising bone-marrow mesenchymal cell adhesion, proliferation, and differentiation.[48–50]

Surface hardness and wear resistance

Several studies have discussed the surface characteristics of titanium implant abutments and suggested that instruments and materials used during oral prophylaxis procedures and maintenance programs alter titanium alloy surfaces.[51,52] Enhanced wear resistance and abrasive hardness are described as important advantages of TiN/ZrN film coatings and, therefore, are suggested to improve the surface properties of pure titanium. In vitro investigations have demonstrated an improved abrasion resistance of TiN samples when compared to uncoated titanium controls.[53–55]

Investigations have also evaluated TiN coating hardness and determined TiN hardness to be within a range of 15 to 26 GPa.[56,57] In addition, authors have estimated that nitride coatings can increase hardness of pure titanium by approximately 10 times (TiN Vickers hardness of 1300).[53]

Optical properties

TiN, when applied to a titanium surface, produces a natural phenomenon known as "light interference" and appears as a yellow color[58] (Fig. 1). An in vitro investigation has shown that TiN coatings can be obtained in a range of compositions and colors depending on the stoichiometry (ratio between the relative quantities of substances taking part in a reaction or forming a compound, in this case, titanium and nitrogen).[25] From the colorimetric point of view, TiN color coordinates were calculated in terms of dominant wavelength (which determines the color hue) and purity (which determines the saturation of color). Lousa et al[25] found that a dominant wavelength of 580 to 582 nm was obtained for all the TiN samples, very close to that of pure gold reference spectrum (579 nm wavelength). Additionally, a purity (color saturation) of 0.84 was obtained, which, according to the authors, approaches the color purity corresponding to the reflectance of standard pure gold (0.91).

The optical properties of newly developed esthetic coatings were also evaluated by Pecnik et al.[59] Three different coating systems (Ti-ZrO_2, Ti-Al-ZrO_2, and Ti-Ag-ZrO_2) were deposited on titanium substrates of different roughness (polished, machined, and sand-blasted) interference colors (pink, yellow, and white) and mucosa thickness (1 mm, 2 mm, and 3 mm). Pink and yellow color coatings showed positive and partially significant overall color (chroma) change (ΔE) in the green-red (Δa) and blue-yellow (Δb) axis, and were considered by the authors as advantageous to obtain an improved peri-implant soft tissue appearance. Similar results were reported by Ishikawa-Nagai et al,[60] where light pink and light orange showed improved esthetic outcomes.

Limitations

Some investigators have outlined concerns when TiN hard coatings are applied to metal alloys used in dentistry. Studies have shown that when TiN film coatings are deposited by PVD and CVD (chemical vapor deposition), possible detachment of TiN/ZrO_2 coatings from the metal substrate surface of transmucosal implant abutments can occur.[61] Pecnik et al[59] indicated that ZrO_2 thin films detached easier from polished Ti samples, and suggested, in accordance with Yang et al[62] that thin film coatings would adhere better on machined or sand-blasted rather than on polished titanium surfaces. Another suggested possible explanation for this delamination was provided by Tong et al[63] who reported that this phenomenon can occur due to inadequate adhesive strength between the TiN film when deposited on pure titanium. The low surface hardness of titanium (microhardness of approximately 200 HV) was unable to support the hard TiN film coating (microhardness of more than 400 HV).

Although possible detachment of TiN surface layer from the metal substrate is considered a disadvantage, the evidence is not conclusive due to the limited number of clinical investigations. To overcome this limitation, Mengel el al[61] suggested employing low contact pressure when performing oral hygiene procedures on TiN coated abutments. In addition, Tong et al[63] suggested using alternative coating procedures such the Duplex Treatment Technique, which includes the use of plasma nitriding followed by the application of TiN coating to improve the surface hardness of titanium and increase the adherence of the film substrate.

Other reported limitations include the development of localized adverse allergic reactions associated with the use of TiN coated transmucosal abutments. Although TiN coating is described as biochemically stable,[64] a clinical report shows TiN as being the possible cause of an allergic contact stomatitis in a patient treated with TiN implant abutments used to support a fixed dental prosthesis.[65] The authors reported that after abutment insertion, the patient complained of pain and discomfort, and the mucosa adjacent to the TiN abutments was erythematous. However, 1 month after TiN abutment removal and insertion of titanium healing abutments, the mucosa appeared healthy and all signs and symptoms had disappeared. Patch tests disclosed a positive reaction to TiN coated abutments. To the best of the authors knowledge, this is the only report describing this type of clinical event.

Clinical applications of titanium nitride coated abutments

The available literature evaluating clinical outcomes associated with the use of TiN abutments is scarce and, to date, there are no long-term randomized clinical trials published. However, the present investigation shows that promising short-term clinical data has been reported when related specifically to the mechanical behavior and technical complications associated with the clinical use of TiN abutments. The loading capabilities of titanium alloy (ductility and tolerance to compressive and tensile stresses)[4] together with the TiN coating layer surface properties[15,27,28] suggest that the biomechanical behavior of the TiN abutments provides adequate short-term clinical outcomes. In a 3-year prospective clinical investigation, Ferrari et al[66] indicated TiN abutments can be predictably used to restore implant supported restorations in all anterior and posterior locations. The authors found a statistically significant higher success rate (100%) at 3 years for CAD-CAM TiN abutments when compared to one piece CAD-CAM zirconia abutments (82.2%).

Adequate short-term clinical outcomes have also been reported for TiN abutments when related to soft-tissue biocompatibility. Investigations found no significant differences in biologic outcomes, radiographic indices, and short-term survival rates[67] among conventional titanium, TiN-coated, and zirconia abutments.[68] A retrospective study evaluating the effect of TiN/Zr single CAD-CAM abutments on the presence of interproximal papilla in the maxillary anterior region, showed that both types of abutments represent a predictable treatment alternative and appear to improve the esthetic results and the papilla presence in the anterior maxilla.[69] When compared to conventional custom titanium abutments in the anterior maxilla, the same group[70] showed that CAD-CAD TiN and zirconia abutments also enhanced the presence of interproximal papilla.

The influence of abutment material color and peri-implant soft-tissue thickness is reported to significantly influence the esthetic outcome of implant-supported restorations.[71,72] Zirconia abutments show a peri-implant soft tissue color closest to the soft tissues around natural teeth, although this difference has not been considered significant when compared to gold alloy abutments.[73] In addition, yellow and pink abutment coating colors are shown to improve the optical appearance and the lightness of the overlaying mucosa.[59] Promising optical behavior has been reported with CAD-CAM TiN coated abutments and the characteristic gold color of TiN abutments is suggested to be advantageous for abutment soft tissue esthetic integration,[74] especially in anterior esthetic areas with a thin gingival phenotype ($\leq$2 mm).[75]

To date, the vast majority of studies reporting on the use of TiN abutments employ CAD-CAM technology for abutment design and manufacturing.[66,69,70] The principal observed advantages of CAD-CAM manufactured abutments include comparable clinical outcomes to stock abutments,[10] customization, precision of fit, durability, and an enhanced formation of peri-implant soft tissue topography and emergence profile.[76]

Case reports have also been published to illustrate the use of TiN abutments to restore single implants in anterior and posterior locations.[77] According to Ramsey et al[78] the main reasons for choosing TiN abutments, especially in the esthetic zone, include optimal biocompatibility, superior fracture resistance when compared to one-piece zirconia ceramic abutments, adequate wear and corrosion resistance, reduced bacterial adhesion, and excellent esthetic integration with the adjacent soft-tissues.

Taking into consideration the reduced number of clinical investigations but also the advantages of CAD-CAM abutments, the fact that TiN abutments are manufactured using this technology would suggest that custom TiN abutments could constitute a predictable alternative to stock/custom, metal/zirconia abutments. TiN abutments could be a clinically relevant alternative in mechanically challenging but esthetically demanding situations such as excessive restorative vertical height (RVH),[79] areas of high occlusal loads, maxillary anterior areas where nonaxial loads are often observed, implant-supported restorations fabricated on narrow diameter implants,[80] and anterior esthetic areas with thin gingival phenotype, where the use of one-piece zirconia abutments may, otherwise, be contraindicated (Figs 2 to 5).

Discussion

Although the use of TiN hard thin film coating technology on metal alloy substrates has been applied in the medical field to coat orthopedic implants (hip and knee replacement prostheses) for decades,[12,19,81,82] its implementation in implant dentistry is more recent. The number of clinical trials published in peer reviewed journals utilizing TiN implants/abutments is still limited. In this review, these reduced number of clinical investigations supposed a limitation and the review protocol only partially complied with reporting guidelines for the development of protocols of systematic reviews and meta-analysis (PRISMA-P).[83] Therefore, a systematic review and meta-analysis could not be conducted, which can be considered a shortcoming of the current review.

The heterogeneity of the topics analyzed, the design of the preclinical and laboratory publications included in the current review and, the subjectivity inherent when authors selectively evaluate and present the available literature, may add additional limitations to this review in the sense that it may be biased by selective reporting. On the other hand, manual searching and careful reading of referenced preclinical and laboratory publications, facilitated broadening the scope of the initial search strategy. This made the authors include several investigations on such diverse areas as clinical medical orthopedics, material surface coating technology, and behavioral sciences of biomedical/dental materials. This protocol, besides bringing out relevant information on the technical aspects of TiN coated implant abutments, to a certain extent, may have "compensated" the weaknesses and limitations of the present investigation. Nevertheless, reporting the data as objectively as possible, was a primary goal of the authors.

To the best of the author´s knowledge, the first review on titanium nitride coatings in clinical dentistry was published in 1992.[22] More recently, Al-Jabbari et al[15] updated the available evidence on TiN and nitrogen ion implanted coated dental materials, however the implementation of this technology in clinical implant dentistry is relatively recent. Therefore, as a

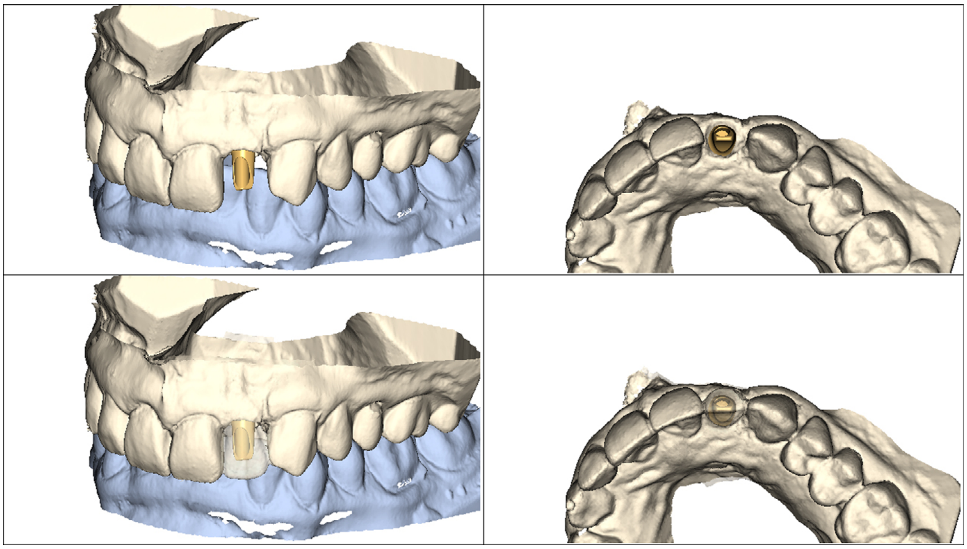

Figure 2 CAD-CAM technology is used to accurately design nitrided abutments based on patient´s specific restorative requirements.

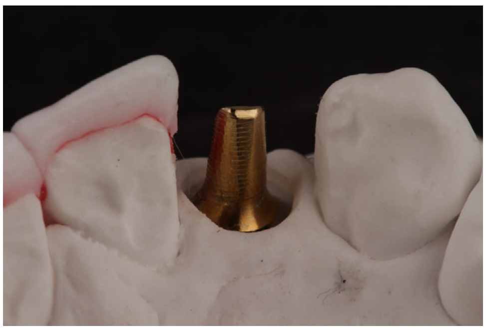

Figure 3 Abutment parameters such as retention, resistance form, restorative margin location, core height, and wall parallelism are optimized before the definitive restoration is fabricated.

Figure 4 Clinical try-in of a custom TiN abutment (maxillary left lateral incisor) to ensure precision of fit prior to definitive restoration fabrication.

Figure 5 Adequate biocompatibility, fracture resistance, and soft tissue esthetic integration suggests that nitrided abutments could represent a predictable alternative to more traditional abutment materials.

second objective, the present review is intended to complement the aforementioned publications by describing new evidence on the physicochemical characteristics, biomechanical properties, and macroscopic surface topography of TiN hard thin film coatings and to highlight the potential applications of this technology and their impact on titanium alloy implant abutment´s biocompatibility, biomechanical properties, and peri-implant soft tissue esthetic integration.

In light of the limited available evidence but also the potential applications of TiN hard thin film coating technology in clinical implant dentistry, there seems to be a need for additional research. At the preclinical level, research is necessary to elucidate the most ideal metal substrate (machined, sand-blasted, or polished titanium alloy) for hard thin film coating, the needed adhesive strength to prevent titanium nitride film detachment after long-term clinical use, and the clinical outcomes derived from these material combinations.

It is worth noting that the majority of recent clinical investigations using TiN coated abutments employ CAD-CAM technology for abutment design and manufacturing.[66–70,74,77,78] Although the level of evidence is low due to the fact that few randomized controlled clinical trials are published, systematic reviews indicate that CAD-CAM abutments demonstrate overall good survival and success rates, and similar, if not superior, clinical outcomes when compared to conventional abutments.[10] Therefore, at the clinical level, additional randomized controlled trials with long-term observational periods are necessary to confirm, not only, the promising short-term clinical outcomes of CAD-CAM nitride coated implant abutments, but also the advantages of custom abutments over stock abutments.

Conclusions

The combination of adequate clinical outcomes and reliability of titanium alloy abutments has led titanium to be the preferred material for custom implant abutment fabrication. Although published research and reported clinical outcomes on TiN prosthetic abutments is still limited, the available biomedical research as well as mechanical engineering tests, in vitro investigations, and short-term clinical trials have, to date, reported promising mechanical, biological, and esthetic outcomes for TiN abutments. However, further in vitro investigations and long-term randomized clinical trials are needed to validate these initial observations, especially those investigating the most ideal metal substrate (machined, sand-blasted, or polished titanium alloy) for hard thin film coating, the needed adhesive strength to prevent titanium nitride film detachment, and the clinical outcomes derived from these material combinations.

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