applied sciences

MDPI

Article

Peri-Implantitis: A New Definition Proposal Based on Unnatural Spatial Arrangement and Late Mechanical Coupling between Two Cortical Bone Layers during Osseointegration Phase: Part I

Stefan Ihde [1,2], Antonina Ihde [1,2], Olga Sipic [1,2] and Łukasz Pałka [3,*]

[1] Jaipur Dental College, Department for Prosthetics, Maharaj Vinayak Global University, Jaipur 302021, Rajasthan, India; prof@ihde.com (S.I.); antonina.ihde@gmail.com (A.I.); oljasipic@gmail.com (O.S.)
[2] International Implant Foundation, Evidence & Research Department, Leopoldstr. 116, 80802 Munich, Germany
[3] Private Dental Practice, 68-200 Zary, Poland
* Correspondence: dr.lpalka@gmail.com

Abstract: Scientists have been speculating for three decades about the reasons for the occurrence of peri-implantitis around dental implants. Many theories have been proposed since the beginning of 1990. Since then, the dental profession has been exposed to a vast number of peri-implantitis cases, whereas the "disease" had been unknown before this time. However, the situation has not improved because we focus more on how to treat the problem instead of trying to understand it completely. The aim of this paper is to present a purely bone-based explanation for the beginning of the "bone loss" process around already "osseointegrated" implants. Conclusion: There are a number of possible chain reactions of physiological bone response to dental implants which may explain the occurrence of peri-implantitis. Bacteria and "immunological reactions" may not be the main causes of this disease. In the first part, the authors present the principles of bone biology and physiology based on the theories of Donath, Jansen and Frost and transfer them to the field of implantology. They describe the stages of "osseointegration", explaining the subsequent changes in the bone at the implant–bone interface.

Keywords: endosseous implant; rough surface; masticatory forces; bone remodeling; peri-implantitis

Citation: Ihde, S.; Ihde, A.; Sipic, O.; Pałka, Ł. Peri-Implantitis: A New Definition Proposal Based on Unnatural Spatial Arrangement and Late Mechanical Coupling between Two Cortical Bone Layers during Osseointegration Phase: Part I. *Appl. Sci.* **2022**, *12*, 4317. https://doi.org/10.3390/app12094317

Academic Editors: Vittorio Checchi and Andrea Scribante

Received: 27 February 2022
Accepted: 21 April 2022
Published: 25 April 2022

1. Introduction

Peri-implantitis (PI) occurs around rough endosseous dental implants, mostly with modified surfaces (sand-blasted, acid-etched, machine-threaded, etc.) [1–3]. However, the surface modification or roughness alone cannot explain the biological reasons or clinical conditions of its development, nor give any clue of when it actually begins. In contemporary implantology, the term peri-implantitis can be misleading, both to professionals and patients. This is a result of how the term ends: "-itis" suggests inflammation, which subsequently suggests bacterial contamination. As a result, a simple search for obvious bone-derived reasons for that development has been neglected [4]. In order to understand how a titanium implant—one of the greatest achievements in restorative dentistry—can be the sole core of bone resorption, we need to understand on what foundations our understanding of "implantology" and "osseointegration" were created. Branemark et al. first observed in 1970, and later published close to 40 years ago [5], their view on the coexistence of living bone and an implanted foreign body that contained 90% or more Ti, which were so-called implantable Ti or Ti-alloys [6–8]. At the same time, when the mentioned researchers shared their opinions, German researcher Prof. Karl Donath had thought out and published the concept of the "extra-territorialization" of intra-bony cysts

by a surrounding cortical bone [9]. He concluded that the reasons which had led to the creation of cortical bone around the soft-tissue borders of the cyst must be the same as those which lead to the creation of cortical bone around dental implants. Unfortunately, his concept was overlooked at that time. Only recently, in 2020, Albrektsson, who belonged to Branemark's original research team, admitted in one of his papers that "Donath's concept was actually right" and was positively verified by other researchers [10]. Based on his research, Donath came to the following conclusions: "Non-loaded implants" are in contact with the small bone lamellae, which are in turn in contact with the trabecular bone. The small bone lamellae are interrupted by areas of bone marrow or parts of the canal system. Between the bone marrow and the implant surface, there are only two to three cell layers consisting of fibrocytes with collagen, or the implant surface is in direct contact with fat. The bone-free surfaces of the implant contain mono- or multinucleate macrophages. The macrophages on titanium implant surfaces occasionally contain small particles of titanium in the cytoplasm. "Loaded titanium implants" are covered by compact bone, which has only some bone-free areas near Haversian canals [9]. Therefore, Donath had already paved the way towards a bone- and function-derived understanding of various physiological developments around dental implants (including "peri-implantitis"). However, his voice was not understood in the early times of oral implantology when only the "advantages of osseointegration" were praised.

2. Introduction to the Concept with Milestone Questions

If we compare sites that contain loaded teeth to sites that contain implants, we find a stunning similarity: loaded teeth are surrounded in the root area by a cortical (the lamina cribrosa) bone, and this cortical bone transfers loads into the surrounding spongious bone, which develops a load-distributing structure [11]. If teeth are lost or extracted, the internal cortical bone around the former roots will disappear, the crestal bone over the extraction site will close, and later, the outer cortical bone layer will remain uninterrupted [12]. From the "bone's point of view", this seems to be the acceptable steady state. So, subsequent questions arise:

2.1. Why in the Area of Spongious Bone Is a Cortical Layer Created around Intra-Bony Cysts and Implants?

While the two cortical bone layers move relatively against each other, if and while the bone is loaded/deformed, the internal structure (i.e., the spongious bone) shows relocation and deformation (Figure 1). According to Wolff's law, the structure of the spongious bone has been created as a response to the function [13,14].

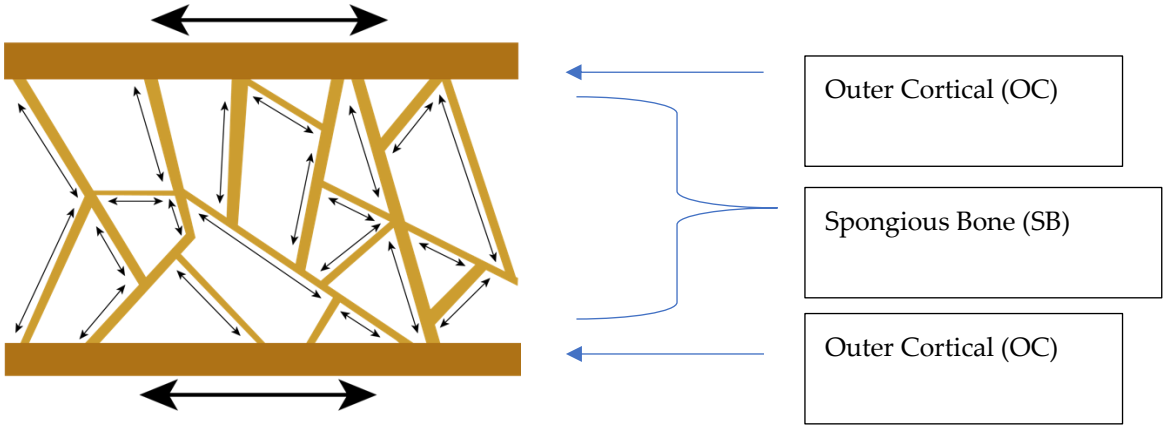

Figure 1. Schematic overview of a long bone under mechanical deformation. Thick double arrows show the deformation of the outer cortical bone (OC), thin double-arrows show the deformation and relative spatial changes in the spongious bone (SB) compartment.

If a cyst, such as that presented in Figure 2 (with the red outer membrane and yellow content), develops inside the spongious part of the bone, a number of vitally important struts of the spongious bone are removed by it. In order to guarantee the overall stability of the bone, new pathways for load transmission have to be built around the cyst, and these pathways sum up to a circumferential inner cortical (IC). This is a purely function-driven process; it serves the aim of keeping the whole bone intact and preventing fracture. The process does not require any immunological component.

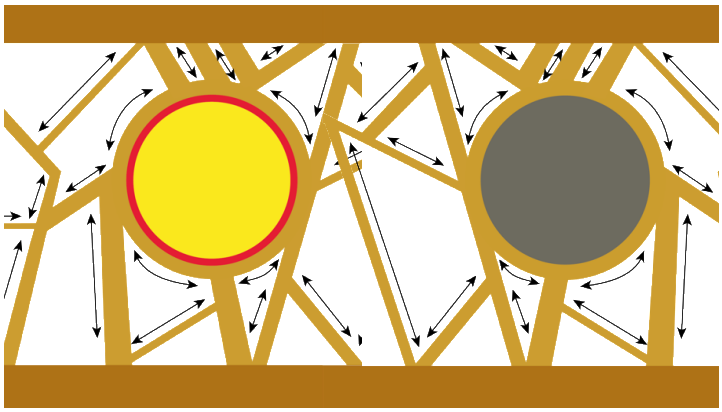

Figure 2. Schematic presentation of a cyst (yellow circle) and an integrated implant (grey circle) inside the bone. The cyst is a foreign body which is surrounded by a cortical bone because it disrupts the continuity of the bone structure. Likewise, the endosseous implant represents such a disruption. Both foreign bodies are extra-territorialized by a cortical bone.

If, instead of the cyst, the solid implant body is inserted into the spongious bone, again, a number of spongious struts are removed, and to keep the integrity of the bone intact, they must be replaced (Figure 2). As soon as the integrated implant is loaded, mastication-induced forces reach the center of the bone, and this leads to a mature and thick internal cortical (IC) bone. Furthermore, we have to remember that the large-diameter (tube-type) implants made from Ti-alloy will not exhibit any isoelastic behavior with the surrounding bone [15]. Masticatory forces transmitted through metallic implants are in general transmitted to the outer cortical layers of the bone. Load transmission and bone formation between the implants have not been described. It seems that the bone also does not use the (theoretically possible) direct way through the implant for its internal load transmission (Figure 2), and this is why the reduction in the bone (atrophy) in the case of PI occurs.

2.2. What Is the Nature of the Bone-to-Implant Connection?

In the original experiment related to osseointegration, Branemark et al. [16,17] found that the bone's surface had grown towards the titanium device which had been placed inside the bone. Both surfaces were congruent and their device was polished. However, it was very easy to detach them from each other as the surfaces were not glued. Later, the endosseous surfaces of oral implants started being roughened with the intention to increase the surface contact area and to thereby increase the load transmission possibilities. What actually is increased with these surfaces is the removal torque [18–20]. Salvi and Lang reviewed existing paradigms in implant dentistry, and on the basis of their findings concluded that bone-to-implant contact is greater for implants with rougher surfaces and/or they require greater forces to be separated from the bone than implants with smoother surfaces [21]. With the older polished implants (without macro-retention like bone-bays) used at that time (the 1970s/1980s), it was possible to remove the implant, while the peri-implant cortical layer remained intact and in the bone, and likewise, the same implant could have been screwed back in and put back into function [20,22]. This is not possible with the present roughened implant devices, but this should not lead to the assumption

that the bone bonds to such implant surfaces. This is clearly visible during the process of preparing histology specimens and how easily the "well and long-term integrated" implant body detaches from the surrounding bone, i.e., the "osseointegarted" metallic part just falls off the bone as soon as macro-retention is taken away [22]. Between 1982 and 1987, Albrektsson et al. conducted a series of experiments, in which they demonstrated that it is possible to osseointegrate commercially pure titanium, alloys of titanium with zirconium and niobium metals, whereas it was not possible for gold or stainless steel [23]. Today, we put more interest in the type and stability of the oxide layer created at the implant surface and its interaction with bone.

2.3. Is There a Mechanic Coupling of Different Cortical Bones during or after Osseointegration?

The existing theories about "osseointegration" focus exclusively on the border between the implant's surface and the bone [16–18]. We suggest, however, focusing on later developments which take place after the bone–implant force system comes under regular function, and during the period while and after the endosseous peri-implant bone has matured.

Natural teeth are surrounded by fibers, and the fibers insert into the "lamina cribrosa", a perforated cortical (IC) bone, which transmits some of the masticatory forces into the surrounding spongious bone (SB), while most of the forces are transmitted to the outer cortical (OC) layer of the jaw bone. The mechanical coupling of these outer and inner cortical layers develops over years during the formation of the teeth. Ihde et al. [24] defined a new systematic terminology for osseofixated implants and suggested that working with the so-called "first cortical" layer is identical with the outer cortical (OC) layer. Since an endosseous vertical cortical (IC) layer seems to be missing in osseofixated implants, the latter cortical layer has not yet been defined.

If a classic two-stage implant is inserted into the jaw bone, the surgeon's goal is to achieve primary stability by pressing it into the drill hole. Part of this stability is achieved by compressing the trabecular bone and by pressing the first cortical layer against the implant body [25]. In many implants, specific threads are designed together with additional notches in the apical part of the implant for blood clot and subsequential callus formation [26]. As a result of the implant design (for example, reverse conical neck implants) and the use of a countersink drill, this connection between the implant and the outer cortical cannot be expected to be fully tight immediately following implant placement [27,28], Hence, such implants are covered by a flap or healing screw which creates a sterile compartment for the healing phase.

Inside the bone, points of direct contact between some of the spongious struts and the implant are created during insertion [11]. The more the design of the implant and the drilling procedure leads to the compression of the spongious bone, the more stability is created during the insertion of the implant. Since typical two-stage implants have to provide space for an internal connection (to the abutment), the implant provides almost parallel walls in the top part and conicity only in the apex area. Thereby, the chances of achieving a lot of stability through compression are low.

After "osseointegration" has occurred, the collar zone of the implant towards the first cortical layer is sealed with the new bone, and inside the spongious bone, new struts find contact with the implant's surface. The next step is the formation of a full cortical bone around the endosseous implant surface until a state shown in Figure 3 has been reached [29].

After the implant is axially loaded on intrusion (vertical arrows show the direction of loading), the thickness of the cortical layer around the implant's surface increases, and also, the first cortical layer gains thickness (Figure 3). The angle between the surface of the implant and the first cortical layer is about 90 degrees, as presented in Figure 3.

From the "bone's point of view", such an angle resembles a very strong convexity. The fact that the bone is in direct contact with the implant does not improve the situation. As mentioned earlier, the bone is not glued to the implant surface.

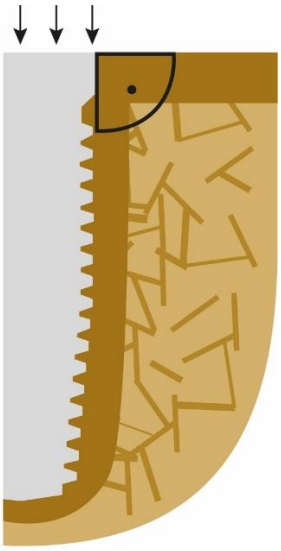

Figure 3. After osseointegration, the endosseous implant surface is covered by bone in direct contact. This bone corticalizes. Bone and implant are loaded on intrusion, and the angle between the outer cortical and inner cortical is sharp.

2.4. What Is the Significance of the Curvature of Loaded Cortical Bone Areas?

Physicians have observed that fractures which heal at a non-natural angle tend to straighten by themselves, and this observation has been used for many years as an example of mechanical adaptability in action. A simple hypothesis to explain this phenomenon was proposed by Jansen [30], reiterated by Bassett [31], and by others since. This hypothesis recognizes that if the bent bone is to be straightened, bone must be removed from the convex side and apposition must occur on the concave side. We have transferred this pattern to the situation around the conventional dental implant. It is expected to happen all around the implant and especially if the diameter of the implant is large. Bassett [31] pointed out that a long bone with an angular deformity would be straightened if compressive end loads produced bending stresses that induced these activities on its external surfaces [31]. When bones are mechanically deformed, they become electrically polarized via two mechanisms: firstly, the ionic fluids in the calcified matrix are forced to move about, creating "streaming potentials" [32]; and secondly, the collagen molecules in the bone tissue are "piezoelectric", so that they exhibit a dipole moment when strained [33]. The relative roles of these two phenomena in producing "stress-generated potentials" in bone are unclear, but it is well established, for example, when the bone is bent, that the concave surface becomes negatively charged and the convex surface becomes positively charged. A cortical under tension loses mineralization (i.e., disuse osteoporosis develops), while a bone under pressure increases its mineralization. If we refer to Frost's flexural neutralization theory [34], which says that stress levels above a minimum effective stress activate the response, this means that not every patient with the described configuration between an implant and the IC and OC will develop PI. It also clearly means that every patient that has been treated with this type of medical device (modified surfaced implants with a large endosseous diameter) meets all conditions for developing PI. Experience shows that the pattern of chewing is one of the decisive elements for its development because this aspect of oral function determines how much the convex surface of the coupling area between IC and OC increases its convexity.

Figure 4 illustrates the stages of the implant's bony environment and the angles at the first (outer) cortical layer.

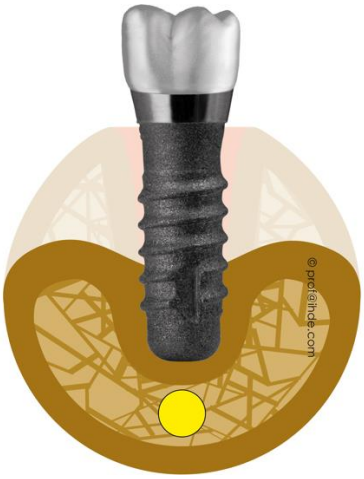

Figure 4. Due to the mechanisms of natural bone resorption (falsely addressed as peri-implantitis), the crestal angles created by the outer cortical layer of the bone and the vertical cortical layer (see Figure 3) are resolved. After the bone has arranged this acceptable morphology and after angles are flattened, no further bone loss is required.

3. Conclusions

Based on the presented findings and clinical observation of the bone around a two-stage dental implant, we can draw the following conclusions: it takes more than 6 months (bone healing and remodeling) for the bone around the implant sites to fully heal [35]. Fully healed bone indicates the development of the inner cortical (IC) layer around the implants, as well as mechanical coupling between the inner and the outer cortical layer. Until endosseous implants are able to transfer masticatory loads to the outer cortical (OC) layer and into the first cortical layer, the new cortical layer on the rough implant surface (from Donath's "extraterritorialisation") must be fully consolidated, mineralized and functionally fused to the first cortical layer, until load transmission can happen. The angle between cortical bone layers plays an important role in the stability of assembly under intrusive and extrusive masticatory forces.

Author Contributions: Conceptualization, S.I. and A.I.; methodology, O.S.; validation, S.I., A.I., O.S. and Ł.P.; formal analysis, S.I. and Ł.P.; investigation, A.I. and O.S.; resources, S.I. and A.I.; data curation, S.I., A.I. and O.S.; writing—original draft preparation, S.I. and Ł.P.; writing—review and editing, S.I., A.I., Ł.P. and O.S.; visualization, S.I. and A.I.; supervision, Ł.P.; project administration, S.I., A.I. and O.S.; funding acquisition, S.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Caccianiga, G.; Rey, G.; Caccianiga, P.; Leonida, A.; Baldoni, M.; Baldoni, A.; Ceraulo, S. Rough Dental Implant Surfaces and Peri-Implantitis: Role of Phase-Contrast Microscopy, Laser Protocols, and Modified Home Oral Hygiene in Maintenance. A 10-Year Retrospective Study. *Appl. Sci.* **2021**, *11*, 4985. [CrossRef]
2. Teughels, W.; Van Assche, N.; Sliepen, I.; Quirynen, M. Effect of material characteristics and/or surface topography on biofilm development. *Clin. Oral Implants Res.* **2006**, *17*, 68–81. [CrossRef] [PubMed]
3. Saulacic, N.; Schaller, B. Prevalence of Peri-Implantitis in Implants with Turned and Rough Surfaces: A Systematic Review. *J. Oral Maxillofac. Res.* **2019**, *10*, e1. [CrossRef] [PubMed]

4. Fragkioudakis, I.; Tseleki, G.; Doufexi, A.E.; Sakellari, D. Current Concepts on the Pathogenesis of Peri-Implantitis: A Narrative Review. *Eur. J. Dent.* **2021**, *15*, 379–387. [CrossRef]
5. Branemark, P.; Zarb, G.A.; Albrektsson, T.; Rosen, H. Tissue-Integrated Prostheses. Osseointegration in Clinical Dentistry. *Plast. Reconstr. Surg.* **1986**, *77*, 496–497. [CrossRef]
6. *ISO 5832-2:2018*; Implants for Surgery—Metallic Materials—Part 2: Unalloyed Titanium. International Organization for Standardization: Geneva, Switzerland, 2018. Available online: https://standards.iteh.ai/catalog/standards/cen/00cb7dc7-2dc4-4a66-ac8b-bcee30d74472/en-iso-5832-2-2018 (accessed on 21 January 2022).
7. *ISO 5832-3:2016*; Implants for Surgery—Metallic Materials—Part 3: Wrought Titanium 6-Aluminium 4-Vanadium Alloy. International Organization for Standardization: Geneva, Switzerland, 2016. Available online: https://www.iso.org/standard/66637.html (accessed on 21 January 2022).
8. *ASTM F136-13(2021)e1*; Standard Specification for Wrought Titanium-6Aluminum-4Vanadium ELI (Extra Low Interstitial) Alloy for Surgical Implant Applications (UNS R56401). ASTM International: West Conshohocken, PA, USA, 2021. Available online: https://www.astm.org/f0136-13r21e01.html (accessed on 21 January 2022).
9. Donath, K.; Laass, M.; Günzl, H.J. The histopathology of different foreign-body reactions in oral soft tissue and bone tissue. *Virchows Arch. A Pathol. Anat. Histopathol.* **1992**, *420*, 131–137. [CrossRef]
10. Albrektsson, T.; Wennerberg, A. On osseointegration in relation to implant surfaces. *Clin. Implant Dent. Relat. Res.* **2019**, *21* (Suppl. S1), 4–7. [CrossRef]
11. Iezzi, G.; Mangano, C.; Barone, A.; Tirone, F.; Baggi, L.; Tromba, G.; Piattelli, A.; Giuliani, A. Jawbone remodeling: A conceptual study based on Synchrotron High-Resolution Tomography. *Sci. Rep.* **2020**, *10*, 3777. [CrossRef]
12. Devlin, H.; Sloan, P. Early bone healing events in the human extraction socket. *Int. J. Oral Maxillofac. Surg.* **2002**, *31*, 641–645. [CrossRef]
13. Wolff, J. *The Law of Bone Remodeling*; Translation of the German 1892 Edition; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 1986.
14. Frost, H.M. Wolff's Law and bone's structural adaptations to mechanical usage: An overview for clinicians. *Angle Orthod.* **1994**, *64*, 175–188. [CrossRef]
15. Robau-Porrua, A.; Pérez-Rodríguez, Y.; Soris-Rodríguez, L.M.; Pérez-Acosta, O.; González, J.E. The effect of diameter, length and elastic modulus of a dental implant on stress and strain levels in peri-implant bone: A 3D finite element analysis. *Bio-Med. Mater. Eng.* **2020**, *30*, 541–558. [CrossRef] [PubMed]
16. Branemark, P.I. Vital microscopy of bone marrow in rabbit. *Scand. J. Clin. Lab. Invest.* **1959**, *11* (Suppl. S38), 1–82. [PubMed]
17. Branemark, P.I. Bone marrow, structure and function. *Adv. Microcirc.* **1964**, *1*, 1–42.
18. Barfeie, A.; Wilson, J.; Rees, J. Implant surface characteristics and their effect on osseointegration. *Br. Dent. J.* **2015**, *218*, E9. [CrossRef] [PubMed]
19. Esposito, M.; Felice, P.; Barausse, C.; Pistilli, R.; Grandi, G.; Simion, M. Immediately loaded machined versus rough surface dental implants in edentulous jaws: One-year postloading results of a pilot randomised controlled trial. *Eur. J. Oral Implantol.* **2015**, *8*, 387–396. [PubMed]
20. Albrektsson, T.; Brånemark, P.I.; Hansson, H.A.; Lindström, J. Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. *Acta Orthop. Scand.* **1981**, *52*, 155–170. [CrossRef]
21. Salvi, G.E.; Lang, N.P. Changing paradigms in implant dentistry. *Crit. Rev. Oral Biol. Med.* **2001**, *12*, 262–272. [CrossRef]
22. Linder, L.; Obrant, K.; Boivin, G. Osseointegration of metallic implants. II. Transmission electron microscopy in the rabbit. *Acta Orthop. Scand.* **1989**, *60*, 135–139. [CrossRef]
23. Albrektsson, T.; Albrektsson, B. Osseointegration of bone implants. A review of an alternative mode of fixation. *Acta Orthop. Scand.* **1987**, *58*, 567–577. [CrossRef]
24. Ihde, S.; Ihde, A.; Lysenko, V.; Konstantinovic, V.; Palka, L. New systematic terminology of cortical bone areas for osseo-fixated implants in strategic oral implantology. *JJ Anat.* **2016**, *1*, 71–77.
25. Martinez, H.; Davarpanah, M.; Missika, P.; Celletti, R.; Lazzara, R. Optimal implant stabilization in low density bone. *Clin. Oral Implants Res.* **2001**, *12*, 423–432. [CrossRef] [PubMed]
26. Brunski, J.B. In vivo bone response to biomechanical loading at the bone/dental-implant interface. *Adv. Dent. Res.* **1999**, *13*, 99–119. [CrossRef] [PubMed]
27. Yamanishi, Y.; Yamaguchi, S.; Imazato, S.; Nakano, T.; Yatani, H. Influences of implant neck design and implant-abutment joint type on peri-implant bone stress and abutment micromovement: Three-dimensional finite element analysis. *Dent. Mater.* **2012**, *28*, 1126–1133. [CrossRef]
28. Dávila, E.; Ortiz-Hernández, M.; Perez, R.A.; Herrero-Climent, M.; Cerrolaza, M.; Gil, F.J. Crestal module design optimization of dental implants: Finite element analysis and in vivo studies. *J. Mater. Sci. Mater. Med.* **2019**, *30*, 90. [CrossRef] [PubMed]
29. Albrektsson, T.; Chrcanovic, B.; Östman, P.O.; Sennerby, L. Initial and long-term crestal bone responses to modern dental implants. *Periodontology 2000* **2017**, *73*, 41–50. [CrossRef] [PubMed]
30. Jansen, M. *On Bone Formation: Its Relation to Tension and Pressure*; Longmans, Green and Co.: London, UK, 1920.
31. Bassett, C.A. Electrical effects in bone. *Sci. Am.* **1965**, *213*, 18–25. [CrossRef]
32. Eriksson, C. Streaming potentials and other water-dependent effects in mineralized tissues. *Ann. N. Y. Acad. Sci.* **1974**, *238*, 321–338. [CrossRef]

33. Fukada, E.; Yasuda, I. On the Piezoelectric Effect of Bone. *J. Phys. Soc. Jpn.* **1957**, *12*, 1158–1162. [CrossRef]
34. Frost, H.M. Bone's mechanostat: A 2003 update. *Anat. Rec. A Discov. Mol. Cell. Evol. Biol.* **2003**, *275*, 1081–1101. [CrossRef]
35. Roberts, W.E. Bone tissue interface. *J. Dent. Educ.* **1988**, *52*, 804–809. [CrossRef]