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Mechanical Effects of Implant-tooth Rigid Connection by a Fixed Partial Denture: A 3d Finite Element Analysis.

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Abstract - *This study investigated the mechanical behaviour of tooth-implant fixed partial dentures by three-dimensional Finite Element Analysis. Titanium implants of various length and diameter were rigidly connected to a premolar either by two connected ceramic crowns or by a three unit Fixed Partial Denture. The implant acted like the fulcrum of an orthodontic device inducing tooth intrusion. Bone stresses appeared around the neck of the implant. Implant and abutment's stresses were meaningfully less intense with high diameter and low span. Implant length was a less influencing parameter. The use of wide-bodied implants is recommended in selected cases of short-span fixed partial dentures.*

KEY WORDS: Fixed Partial Denture, Prosthodontics, Implant, Intrusion, Stress, Finite element analysis

INTRODUCTION

The presence of natural teeth and implants is of interest for supporting Fixed Partial Denture (FPD)[1, 2] when restoring a partial edentulous patient. Numerous clinical studies report only insignificant adverse effects after splinting periodontally healthy teeth to implants by means of their prosthetic restorations[3-15].

However, the tooth-implant combination can unfortunately be associated with a variety of undesirable clinical sequelae, including bone resorption around the implant neck, bone fracture, fracture of attachment screws, loosening of attachment screws, cement failure and intrusion of the abutment teeth[8, 9, 16-21].

These severe outcomes underline the importance of understanding the effects of an implant to tooth connection. Teeth and implants have different mobility patterns as teeth are attached by the periodontal ligament that allows 50-200 µm movements, and implants are rigidly anchored within the alveolus (only 10 µm movements attributed to bone flexibility)[22-24]. Stress and strain patterns in the bone surrounding an implant are consequently different when compared with a natural tooth under masticatory forces[4, 22, 24, 25].

According to some authors, the root intrusion of the abutment teeth could be either avoided by a completely rigid connection [13, 19, 26], or by a periodic differential occlusal adjustment procedure, which would re-establish a long-term balance of loading between individual implant- and tooth-supported FPD within the same arch [27, 28]. The cause of the intrusion of abutment teeth combined with implants for FPDs remains unknown [8, 17], and is probably multifactorial. Many factors have been proposed, such disuse atrophy, debris impaction, impaired rebound memory, and mechanical binding[17, 29, 30].

A three-dimensional finite element analysis (3D FEA) is a computer-based method used to calculate and visually represent stresses and strains in complex structures, which are subjected to simulated loads. The calculations require knowledge of the mechanical properties of the materials, such as Young's modulus (E) and Poisson's ratio (ν). This numerical stress analysis technique is widely used today in studying biomechanical problems in dental implantology[31].

In this in vitro study, it was hypothesized that implant design (length and diameter) and span length may influence the mechanical behaviour of the implant-tooth supported FPD. The purpose was thus to examine the stress distribution under static vertical load for a better understanding of the observed clinical outcomes.

MATERIALS AND METHODS

The software package used in this study was CADSAP® (CADLM, France), French version of SUPERSAP (ALGOR® Interactive Systems, USA), and ran on a compatible PC. A 3D modelling assuming linear elasticity was undertaken. The material data (Young's modulus, E; and Poisson's ratio, ν) used in the calculations are presented in Table 1.

In our study, implant-tooth supported FPDs designs were evaluated in a case of partially edentulous mandible with distal extension. It was assumed that the second premolar and/or the first molar were lost. The abutment tooth was a single-rooted premolar (Fig.1) surrounded by a 0.2 mm periodontal ligament. The titanium implant carried a titanium abutment (Fig.1), which was supporting a premolar crown. It was assumed to be embedded at its base and completely integrated. Implant and tooth were in the centre

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Table 1. *Materials' Elasticity Modulus (E, Young's modulus in GPa) and Poisson Proportions (ν, Poisson's ratio), as previously described*[28, 53].

Material Properties	*titanium*	*ceramic*	*dentin*	*cancellous bone*	*periodontal ligament*
Young'smodulus	117	96	18.6	1	0.001
Poisson's ratio	0.33	0.28	0.35	0.35	0.45

Table 2. *Twelve models were realized. For each prosthetics configuration (two connected crowns or three unit FPD), implants were varying in length (12, 10 and 8mm) and diameter (4 and 5 mm).*

Implants	*2 connected crowns*			*3 unit FPD*		
Diameter / Length	*12 mm*	*10 mm*	*8 mm*	*12 mm*	*10 mm*	*8 mm*
4 mm	M1	M2	M3	M7	M8	M9
5 mm	M4	M5	M6	M10	M11	M12

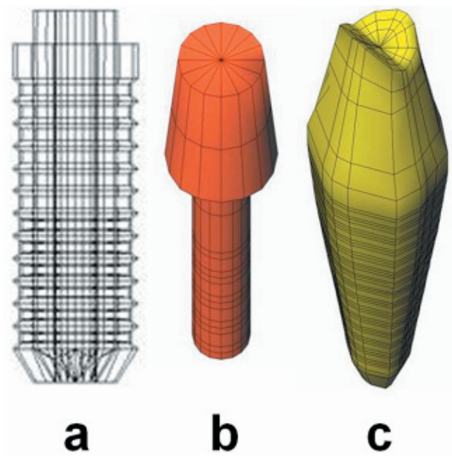

Figure 1. *Implant and tooth models.*

a- Titanium implant (no particular trademark),
b- Titanium abutment (diameter adapted to the implant),
c- Prepared single-rooted mandibular premolar.

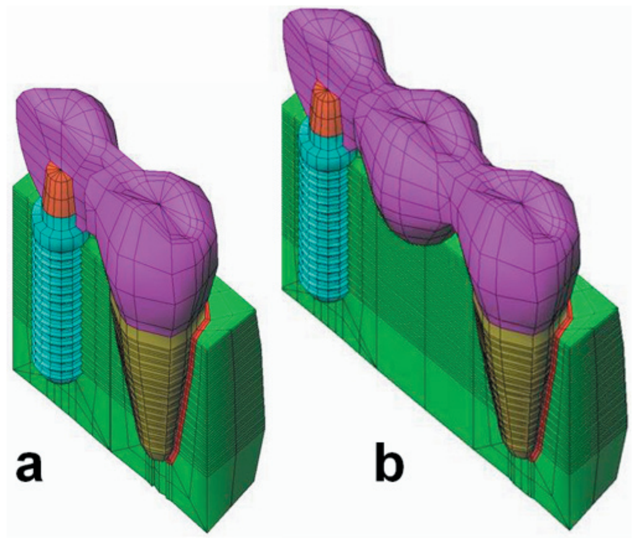

Figure 2. *Assembled models of the compared prosthetic configurations (sectional planes; green: bone, blue: implant, orange: abutment, yellow: tooth, red: periodontal ligament, violet: FPD).*

a- Two connected premolar crowns,
b- Three unit premolar FPD.

of a bony structure, and connected by an all ceramic FPD. General rules were applied for the preparation of natural teeth and creation of ceramic restorations. Between the cemented parts, zinc phosphate thickness was assumed to be 50 µm. Twelve models were compared (Tab.2). Six implants were modelled, varying in length (12, 10 and 8 mm) and diameter (4 and 5 mm). Two prosthetic configurations were considered (Fig.2): two connected crowns or a 3 unit FPD. The assembled models were constituted of about 10 000 brick elements. FPDs were mechanically loaded at their occlusal surface with a defined force of 100 N. This study is comparative. Therefore, the outcomes were not affected by some features arbitrarily chosen, such as intensity of strength applied to the occlusal surface, bone mechanical properties or geometrical configuration of the implant.

Three main parameters were calculated: tooth and implant displacements, distribution and intensity of stress within the implant, abutment and bone. Shearing forces were selected in order to point out areas most intensely subjected to Von Mises stresses (high stresses in red and low stresses in blue).

Compression stresses potentially lead to bone resorption, while tensile stress can be responsible for implant components failures. When indicated, the distribution of compressive or tensile stresses was represented as iso areas showing mean stresses in Pascals. Red and orange indicated areas subjected to high-intensity tensile stresses. Purple and blue indicated high-intensity compressive stresses.

RESULTS

Displacements in bone

The tooth underwent a main movement of intrusion, combined to a secondary movement of rotation whose centre was located roughly in the neck area of the implant. This displacement occurred independently of implant geometry or tooth-implant distance. The dental displacement was significantly more important when the distance between tooth and implant increased (Fig.3a and 3b).

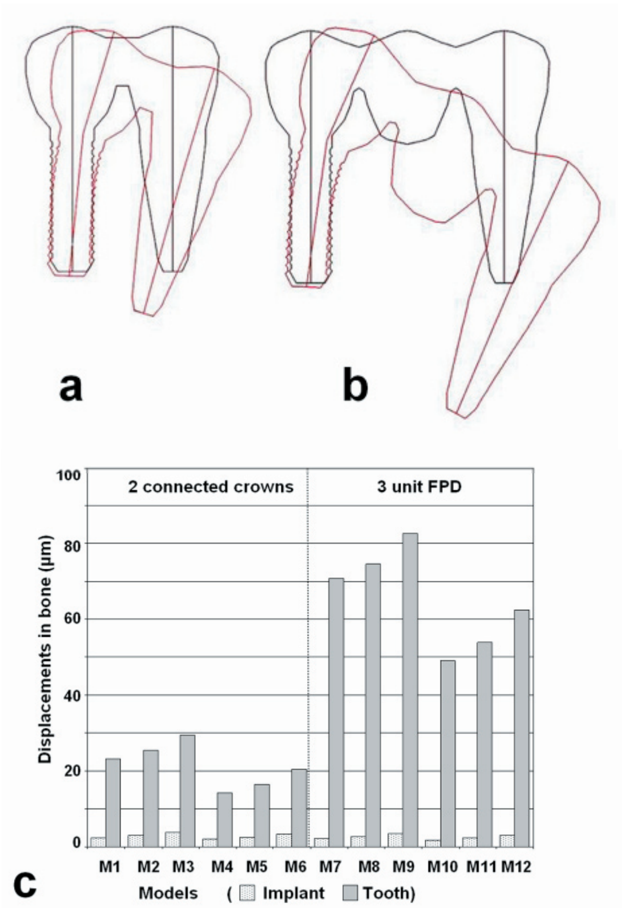

Figure 3. *Tooth and implant displacements (magnified) in bone during occlusal loading. The tooth-implant association underwent a global movement of forcing in the bone, combined to a rocking motion on the hand of the weakest support, the tooth.*

a- Two connected crowns,
b- Three unit FPD.
c- Teeth and implant movements according to the different models. The tooth intrusion increased with the tooth-implant distance, with small implant diameters and slightly with short implant lengths.

Implant components were subject to an intrusion of weak amplitude associated to a bending of the implant. The implant displacement was slightly more marked when the distance between tooth and implant increased (Fig.3a and 3b).

The smallest tooth displacement (12.39 µm) was observed in M4 (2 connected crowns with the biggest implant, 12x5 mm) (Fig.3c). As FEA is a comparison tool, M4 has been chosen for reference (Tab.3). The highest intrusion (+538%) was observed in the 3 unit FPD with the smallest implant (M9, implant 8x4 mm). The intrusion of the tooth increased distinctly with the increase of tooth-implant distance (mean ratio "3 unit FPD/2 connected crowns"= 336%). It also increased with small implant diameter (mean ratio "4 mm implant diameter/5 mm implant diameter"= 143%), and slightly with short implant (mean ratio "8 mm implant length/12 mm implant length"= 121%). The implant relative displacements were less important.

Stresses distribution and intensity

Bone stresses around the implant were located in the implant neck area (Fig.4a). Compressive stresses were located in the area facing the tooth, and tensile stresses on the opposite area. Compressive stresses are believed to be the most detrimental type for bone tissue, leading to clinical bone resorption.

The weakest bone compressive stresses (26.1 MPa) were observed in M6 (2 connected crowns, implant 8x6 mm). As FEA is a comparison tool, M6 has been chosen for reference (Tab.4). The highest compressive bone stresses (+186%) were observed in M7 (3 unit FPD, implant 12x4 mm).

Bone stresses intensities (Fig.4b) were distinctly increased by small implant diameters (mean ratio "4 mm implant diameter/5 mm implant diameter"= 178%). It also increased with long tooth-implant distance (mean ratio "3 unit FPD/2 connected crowns"= 150%) and slightly with implant length (mean ratio "12 mm implant length/8 mm implant length"= 106%).

Implant stresses were located in the cervical part (Fig.5a).

The weakest von Mises stresses (34.9 MPa) were observed in M6 (2 connected crowns, implant 8x6 mm). As FEA is a comparison tool, M6 has been chosen for reference (Tab.5). The highest von Mises stresses (+135%) were observed in M7 (3 unit FPD, implant 12x4 mm).

Von Mises stresses intensities (Fig.5b) were increased by long tooth-implant distance (mean ratio "3 unit FPD/2 connected crowns"= 150%) and small implant diameters

Table 3. *Tooth intrusion (µm) and comparison (%) of each model to model M4. M4 has been chosen as the reference (0%) for its lowest amplitude of intrusion.*

Model	*Intrusion (µm)*	*Increase (%)*	*Model*	*Intrusion (µm)*	*Increase (%)*
M1	20.93	+69%	M7	68.62	+453%
M2	22.31	+80%	M8	71.79	+479%
M3	25.59	+106%	M9	79.12	+538%
M4	12.39	0%	M10	47.23	+281%
M5	13.99	+13%	M11	51.37	+314%
M6	17.20	+39%	M12	59.42	+379%

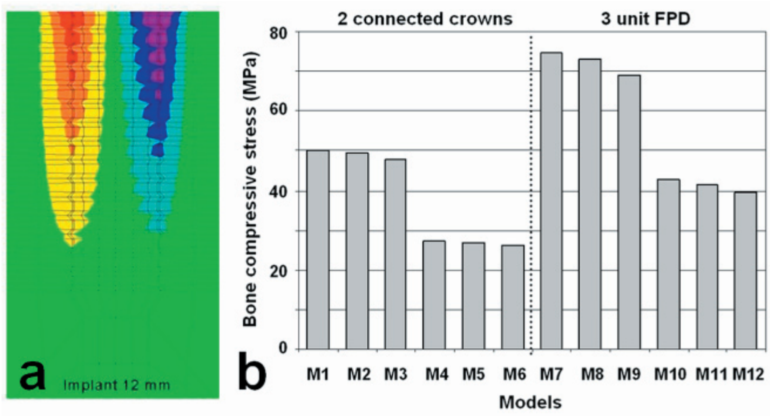

Figure 4. *Distribution and intensity of bone stress.*

a- Example of cervical bone stress distribution observed on M1 (red/orange= tensile stresses, purple/blue= compressive stresses). Compressive bone stresses are located in the cervical area facing the tooth, and are usually linked to clinical resorption.
b- Cervical bone stress intensity (MPa) in the different models. Stresses were reduced by big implant diameter, short tooth-implant distance and short implant length.

Table 4. *Bone compressive stress intensities (MPa) around the neck of the implant and comparison of each model to model M6. M6 has been chosen as the reference (0%) for its weakest stresses.*

Model	*Compressive stress (MPa)*	*Increase (%)*	*Model*	*Compressive stress (MPa)*	*Increase (%)*
M1	50	+91.5%	M7	74.7	+186%
M2	49.4	+89.3%	M8	72.9	+179%
M3	47.9	+83.5%	M9	69.2	+165%
M4	27.3	+4.6%	M10	42.7	+63.6%
M5	26.9	+3%	M11	41.6	+59.4%
M6	26.1	0%	M12	39.5	+51.3%

Table 5. *Von Mises stress intensities (MPa) within implants and comparison of each model to model M6. M6 has been chosen as the reference (0%) for its weakest stresses.*

Model	*Von Mises stress (MPa)*	*Increase (%)*	*Model*	*Von Mises stress (MPa)*	*Increase (%)*
M1	54.9	+57.3%	M7	82.2	+135%
M2	54.4	+55.8%	M8	80.6	+131%
M3	53.2	+52.4%	M9	77.2	+121%
M4	35.9	+2.8%	M10	56.3	+61.3%
M5	35.6	+2%	M11	55.1	+57.8%
M6	34.9	0%	M12	52.9	+51.6%

Table 6. *Von Mises stress intensities (MPa) within abutments and comparison of each model to model M6. M6 has been chosen as the reference (0%) for its weakest stresses.*

Model	*Von Mises stress (MPa)*	*Increase (%)*	*Model*	*Von Mises stress (MPa)*	*Increase (%)*
M1	29.8	+68.4%	M7	42.2	+138%
M2	28.9	+63.3%	M8	40.6	+129%
M3	27.4	+54.8%	M9	37.7	+113%
M4	18.3	+3.4%	M10	27.9	+57.6%
M5	18.1	+2.3%	M11	27.3	+54.2%
M6	17.7	0%	M12	26.1	+47.5%

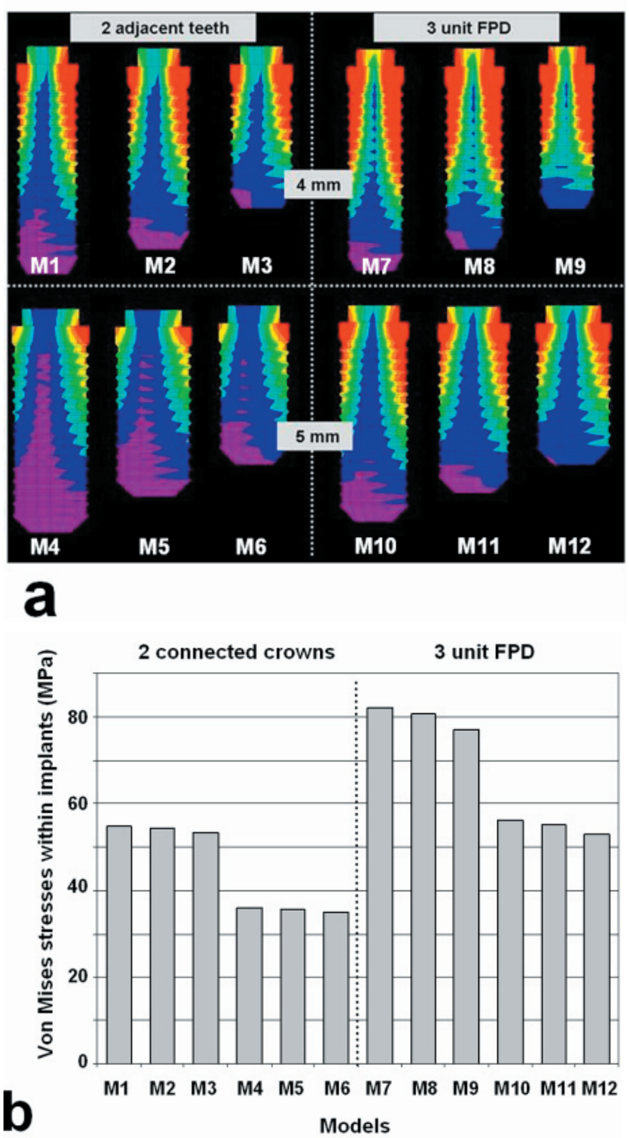

Figure 5. *Distribution and intensity of von Mises stress within implants.*

a-Von Mises stress distribution observed in all models (red= high stresses, blue= low stresses).
b-Von Mises stress intensity (MPa) in the different models. Stresses were reduced by big implant diameter, short tooth-implant distance and lightly by short implant length.

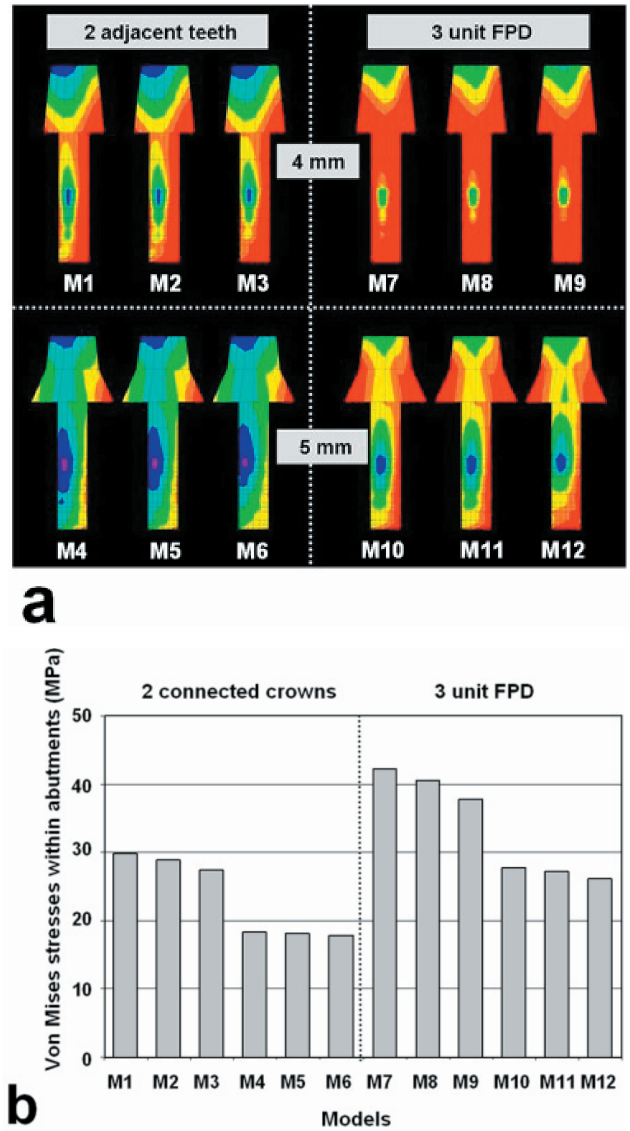

Figure 6. *Distribution and intensity of von Mises stress within abutments.*

a-Von Mises stress distribution observed in all models (red= high stresses, blue= low stresses).
b-Von Mises stress intensity (MPa) in the different models. Stresses were reduced by big implant diameter, short tooth-implant distance and lightly by short implant length.

(mean ratio "4mm implant diameter/5mm implant diameter"= 149%). It also slightly increased with implant length (mean ratio "12 mm implant length/8 mm implant length"= 105%).

Abutments stresses were located in the cervical and apical parts (Fig.6a).

The weakest von Mises stresses (17.7 MPa) were observed in M6 (2 connected crowns, implant 8x6 mm). As FEA is a comparison tool, M6 has been chosen for reference (Tab.6). The highest von Mises stresses (+138%) were observed in M7 (3 unit FPD, implant 12x4 mm).

Von Mises stresses intensities (Fig.6b) were increased by small implant diameters (mean ratio "4 mm implant diameter/5 mm implant diameter"=153%) and long tooth-implant distance (mean ratio "3 unit FPD/2 connected crowns"= 151%). It also slightly increased with implant length (mean ratio "12 mm implant length/8 mm implant length"= 109%).

DISCUSSION

This study was aiming to show the mechanical behaviour of implant-tooth-supported FPDs. The variation of implant's geometry and span's length gave interesting clues to interpret clinical outcomes.

FEA has proved to be an accurate tool for evaluating the mechanical behaviour of implant layouts[31] and convenient as models can easily be modified to accommodate varying hypothesis. The program used in this investigation has several limitations considering the unrealistic simulation of material properties of the structures. This static study assumes that the bone, the tooth, and the periodontal ligament are homogeneous, linear-elastic, isotropic, and does not take into account materials fatigue due to the repeated loads and the complexity of masticatory forces. This method furthermore assumes that the bonding of the bone and the implant is perfect. All static mastication forces applied to FPDs were loaded axially. The mastication forces are however dynamic and oblique relative to the occlusal surface of FPDs. The interference between the implant and the bone is dynamic in reality. Consequently, it is usually impossible to reproduce all the details of natural behaviour. FEA cannot determine criteria for acceptability of stress levels but enables to compare different models and quantify their risks. More work will be yet needed to clarify how well these models match reality.

The tooth undergoes here a main movement of intrusion. The implant is the fulcrum of a device that induces, under the action of the occlusal load, the displacement of the weaker support. As a matter of fact, rigid endosseous implants, because of their immobility, are used by orthodontists to induce dental displacements as intrusions. Their therapies are facilitated and quickened by the use of implants. They are more efficient than dental anchorage. Few mild root resorption at the furcation area or at the root apex have been described after these orthodontic teeth intrusion[32-36], and these iatrogenic problems have been attributed to the forcing bone movement (compression stresses). In our study, the tooth displacement is increased with long tooth-implant distance and with small implant diameter. The length of the implant appeared to be a minor parameter, as the tooth intrusion increased slightly with the implant length decrease. These results corroborate and explain the intrusion of the abutment teeth noted in clinical reports[9, 18, 19, 21].

The most intense bone stresses were located around the neck of the implant in all models. These results are in accordance with other mechanical and computational studies[37-39]. Bone stresses are here distinctly reduced with short tooth-implant distance and big implant diameter. The benefit of wide-bodied implants is demonstrated from a mechanical point of view. The risk of failure compared to regular-diameter implants may be related to the relative relationship of implant diameter and host bone dimensions[40]. Bone stress intensities are slightly reduced by decreasing the implant lengths, as previously described in our laboratory [41].

Implant and abutment's stresses are meaningfully less intense with big diameters and low tooth-implant distance. They are slightly reduced by decreasing the implant length. This theoretical analysis shows that increasing the implant length does not always result in better distribution of stresses to implants and abutments[41].

Other parameters, such as bone quality, must be taken into account before stating on the matter. The understanding of mechanical competence of trabecular bone might reveal further information about the prognosis of alternative treatments with connecting implants to teeth.

The clinical severe outcomes have suggested that alternative treatments without connecting implants to teeth may be indicated[1, 42, 43]. In his clinical study, Naert [44] indicates that major bone loss occurred around implants rigidly connected to teeth. For this reason, when implants and natural teeth are combined, forces on the abutments need to be controlled. Clinical, mechanical and computational studies display some different results that are as yet inconclusive[45]. Cohen and Orenstein[46] suggest to use a non-rigid attachment in the implant crown. The non-rigid connection limits cantilever forces and directs occlusal loads axially in a direction along the long axis of the implant. Recently, Ozcelik and Ersoy[47] suggested after using 2D FEA and photoelastic stress analysis methods a non-rigid attachment should be placed on the implant-supported side. Instead of non-rigid connections, some authors have recommended the use of implants with a stress-absorbing element (intramobile element or stress-breaking element), or an implant with a stress-eliminating space [25, 48-52]. However, there is no consensus about the use of rigid/non-rigid connections or stress-absorbing implants when implant-tooth supported FPDs is planned.

CONCLUSION

This FEA compared implants of different lengths and various diameters connected to natural tooth. This theoretical approach helps to assess risk factors and suggests that:

1. Implant-supported restorations should not be connected to natural teeth, as outcomes showed severe risks of tooth intrusion and bone resorption around the neck of the implant.
2. The use of wide-bodied implants is recommended when implant abutments and natural teeth are both involved to support a prosthetic restoration in some selected cases of short-span FPD.

Bone quality and connection methods stay as important parameters, which must definitively be studied and taken into account.

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