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BIOMECHANICAL STRESS ANALYSIS OF BONE-IMPLANT INTERFACE

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Over the last decade immediate load protocol has been revalued in the field of oral implantology with a view to achieve a simpler implantation protocol. This would lead to relevant advantages, such as a lower invasive impact of implantation and a shorter timing of treatment, with the patient regaining total masticatory functionality within the immediate post operative stage. In order to optimize the immediate load protocol and to foster implant osseointegration, the Italian Implantology School has developed soldering techniques by welding one or more stabilizing bars. Welding techniques allow obtaining a better primary stability in the early post-operatory period in comparison with non-supported implants, as micromovements are reduced and stress/strain distribution at bone-implant interface is more balanced. The present essay "Biomechanical stress analysis of bone-implant interface" is intended to study the distribution of stress/strain exerted by masticatory loads onto the peri-implant bone, with a view to decide whether the bar may be removed by completion of the healing process without relevant impact on bone strain. Secondly, it will be estimated whether the use of two bars undersized in diameter and symmetric to the implant can be compared with the application of one bar only. Finite Element analysis was performed. The results demonstrated that the use of a stiff definitive prosthesis (metal-porcelain) allows to remove the bar after 90 days' recovery, thus avoiding any cosmetic, hygienic and prosthetic contraindication.

Over the last decade immediate load protocol has been revalued in the field of oral implantology with a view to achieve a simpler implantation protocol. This would lead to relevant advantages, such as a lower invasive impact of implantation and a shorter timing of treatment, with the patient regaining total masticatory functionality within the immediate post operative stage. In order to optimize the immediate load protocol and to foster implant osseointegration, the Italian Implantology School has developed soldering techniques by welding one or more stabilizing bars. Welding techniques allow obtaining a better primary stability in the early post-operatory period in comparison with non-supported implants, as micromovements are reduced and stress/strain distribution at bone-implant interface is more balanced (1).

However the role played by a solder bar once osseointegration has completed is still much debated, as it also involves contraindications concerning cosmetic, hygienic and prosthetic results. Particularly, it is difficult to gauge the actual effect of welded titanium bars once the implants are already anchored by a prosthesis with extreme intrinsic stiffness, typically featured with metal framework; secondly, there is not yet complete certainty whether Lorenzon's welding technique –based on the application of one single bar with 1.5-2.0 mm diameter-can be preferred to alternative procedures based on the use of two bars diametrically undersized, which involves direct cosmetic benefits.

The present essay "Biomechanical stress analysis of bone-implant interface" is intended to study the distribution of stress/strain exerted by masticatory loads onto the peri-implant bone, with a view to decide whether the bar may be removed by completion of the healing process without relevant impact on bone strain. Secondly, it will be estimated whether the use of two bars undersized in diameter and symmetric to the implant can be compared with the application of one bar only, as proposed by Dr Lorenzon (2).

Key words:

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Such mission will be pursued by a computational approach, creating the model of a jaw fitted with three implants for the assessment of the stress induced in the peri-implant bone by the application of different types of prostheses and soldering procedures. Analysis results will be used to assess strain energy values. Strain energy –which is an indicator for the stress operated in a given material- is considered as related to bone remodeling stimulus (3, 4).

MATERIALS AND METHODS

The reference model for the analysis was the section of an edentulous mandible, where three screw-retained implants had been inserted. The implants were covered by dental prostheses and were susceptible of further support by welding one or two titanium bars Comparative analyses will be provided according to variations in: bone quality; prosthesis material; number, position and dimension of the solder bar.

As for the methods adopted, Tramonte screws were used with five threads, conical shape, 5 mm external diameter. Three types of prostheses were considered:

- Three implants with vertical parallel axes, mutually soldered through the application of a prosthesis (Fig. 1a);
- Three implants with vertical parallel axes, mutually soldered through the application of a prosthesis supported by a laterally positioned stabilizing bar with a diameter of 1.5 mm (Fig. 1b);
- Three implants with vertical parallel axes, mutually soldered through the application of a prosthesis supported by two stabilizing bars of 1.2 mm in diameter, set symmetrically to the implants (Fig. 1c).

For a more comfortable operation, the prosthesis was modeled in prismatic geometry, with 10x10 mm lateral section. However, such a simplification complied with comparable studies (1, 2).

The mandible section itself is presented as a prismatic solid, with two external layers made of cortical bone, whereas spongeous osseous tissue lies in the central region.

Two different bone qualities were considered (Fig. 2):

- D2 (mm 1.5 cortical bone thickness; mm 17 spongeous bone height; mm 0.5 peri-implant cortical bone);
- D4 (mm 0.2 cortical bone thickness; mm 19.6 spongeous bone height; the mandible was blocked by a joint on the lower surface.

All the materials included in the composition of implants, prostheses and bones were modeled as homogeneous and isotropic materials with a linear elastic behavior. The related mechanical properties are reported in Table I. Two series of analysis will be further shown, where the prosthetic material was changed to palladium alloy or resin. As for the spongeous bone, different values of elastic modulus were considered according to bone quality; particularly, with reference to D4 bone type the value adopted was 1/3 of that considered for D2 type (5).

Each model underwent five different load conditions (Fig. 3):

- Vertical compression load Fz = 800 N applied to the middle of the prosthesis (Load 1)
- Vertical compression load Fz = 800 N + lateral load Fx = 20 N applied to the middle of the prosthesis (Load 2);
- Vertical compression load Fz = 800 N applied to prosthesis edge (Load 3);
- Vertical compression load Fz = 800 N+ lateral load Fx = 20 N applied to prosthesis edge (load 4);
- Vertical compression load Fz = 400 N applied on the prosthesis at the first implant (lateral implant) and vertical load compression Fz = 100 N applied on the prosthesis at the second implant (central implant) (load 5).

Load values were calculated in such a way as to remain within the elastic limit.

The geometric domain of the models was discretized by using 120 000 tetrahedral 10-node elements. Strain energy density (SED) was considered as a reference for the stress at bone-implant interface; SED is in fact an indicator for stress/strain in an elastic material. In literature several studies relate such value with bone remodeling in peri-cervical region, thus assuming an existing range of favorable values: when SED is below the lowest value in the range, the bone proves to suffer reduced stress, thus stimulating resorption and consequently a certain loss in tissue; when SED rises above the highest value in the range, stress/strain becomes overwhelming, thus leading to micro-fractures in the tissue (3, 4).

Analysis rationale

For each and any combination of prosthesis and bone type as well as for every single prosthetic solution (prosthesis only/prosthesis+bar/prosthesis+2 bars) (Table II), five analyses will be reported according to the varying load conditions, for a total of 60 analyses. Analyses will pursue the following aims:

1) Assessment of the effect produced by the bars according to prosthesis material and bone type;

2) Comparison between the data related to the application of two undersized bars and a single bar (the latter responding to Lorenzon's technique).

RESULTS

The present analysis monitored the effect of three parameters on SED distribution at bone-implant interface:

1) Pre-determined prosthetic solution (none/one/two bars), with unvaried prosthesis material and bone type;

2) Bone type (D2 or D4), with unvaried prosthetic solution and prosthesis material;

3) Prosthesis material (palladium alloy or resin), with unvaried prosthetic solution and bone type.

Palladium Alloy Prosthesis

Fig. 4 reports a comparative analysis of SED average values for each of the three implants (interface 2 = central implant; interface 1 and interface 3 = lateral implants) as the different prosthetic solutions vary through the five different load conditions considered (Fig. 3). The reported data refer to D2 bone type, but similar results were also reported for D4.

The results show that, whatever the load condition is, the application of one or two bars produces no relevant

Table I. *Mechanic properties of model materials*

component	Dental implant Bar	Dental Prosthesis		Cortical Bone	Spongeous Bone	
material	Titanium gr. 2	Resin	Palladium Alloy		D2 bone type	D4 bone type
E [GPa]	110	2.3	104	34	13.7	4.4
v [-]	0.37	0.45	0.35	0.26	0.38	

Table II. *Analysis layout*

Prosthesis material	Bone type	Prosthetic solution
Palladium alloy	D2	Prosthesis only
		Prosthesis + bar (1.5 mm diameter)
		Prosthesis + 2 bars (1.2 mm diameter)
	D4	Prosthesis only
		Prosthesis + bar (1.5 mm diameter)
		Prosthesis + 2 bars (1.2 mm diameter)
Resin	D2	Prosthesis only
		Prosthesis + bar (1.5 mm diameter)
		Prosthesis + 2 bars (1.2 mm diameter)
	D4	Prosthesis only
		Prosthesis + bar (1.5 mm diameter)
		Prosthesis + 2 bars (1.2 mm diameter)

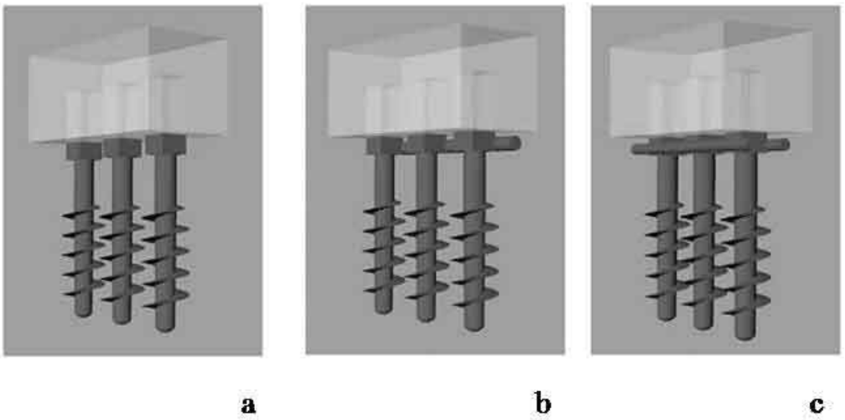


Fig. 1. *Geometrical model of three implants joined by prosthesis (a); Geometrical model of three implants joined by prosthesis and lateral bar (b); Geometrical model of three implants joined by prosthesis and two bars (c).*

variation in terms of SED at the three bone-implant interfaces. This happens since in the analyzed prosthetic solutions the palladium alloy prosthesis produces a stronger joining effect than the two bars do (with the bars made of a similar material in terms of stiffness – see Table I – but undersized in section).

SED distribution at bone-implant interface - clearly shown in the chromatic chart in Fig. 5 (concerning D2 bone type, although similar results were reported for also D4) – indicates that stress/strain concentrates in the bone, in the region surrounding implant necks.

Stress/strain distribution varies in compliance with load conditions: with load types 1 and 2 (load applied to the middle of the prosthesis) the distribution is symmetric, whereas with loads 3-4 (load applied to one of the two lateral implants) and 5 (load applied to both the central implant and one of the lateral implants) the force is mainly transmitted through interface 3, which belongs to the

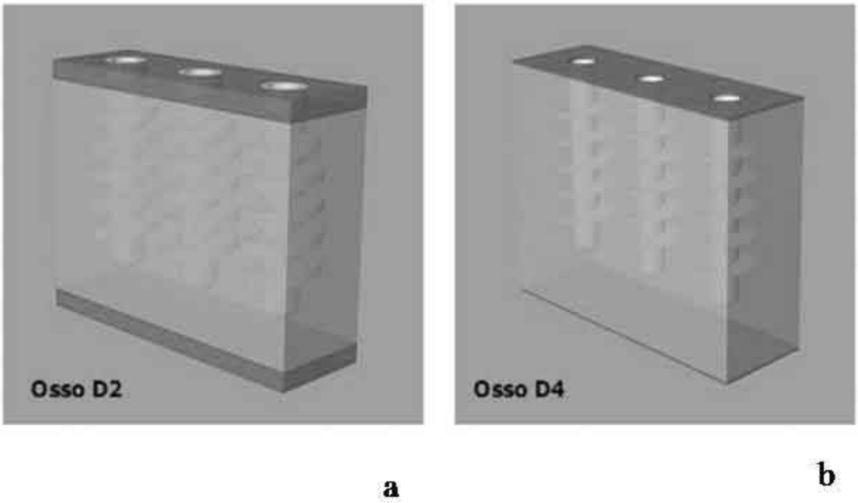
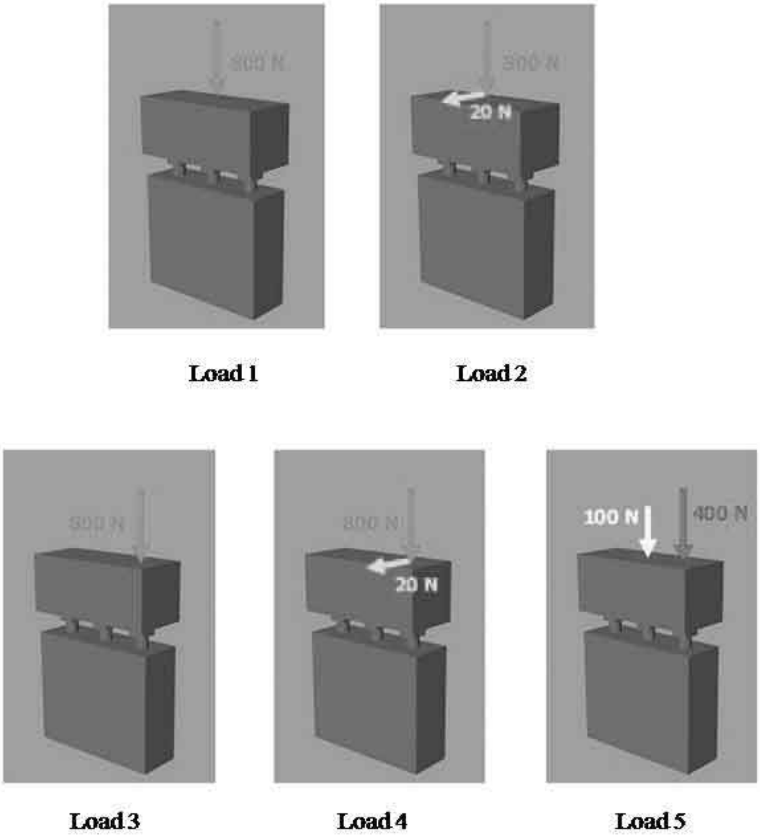


Fig. 2. *Geometrical models of mandible with D2 (a), D4 (b) bones. Spongeous bone is presented in blue color; Cortical bone in red; peri-implant cortical bone in green.*



Load 1 Load 2

Load 3 Load 4 Load 5

Fig 3. *Load conditions used in the analysis*

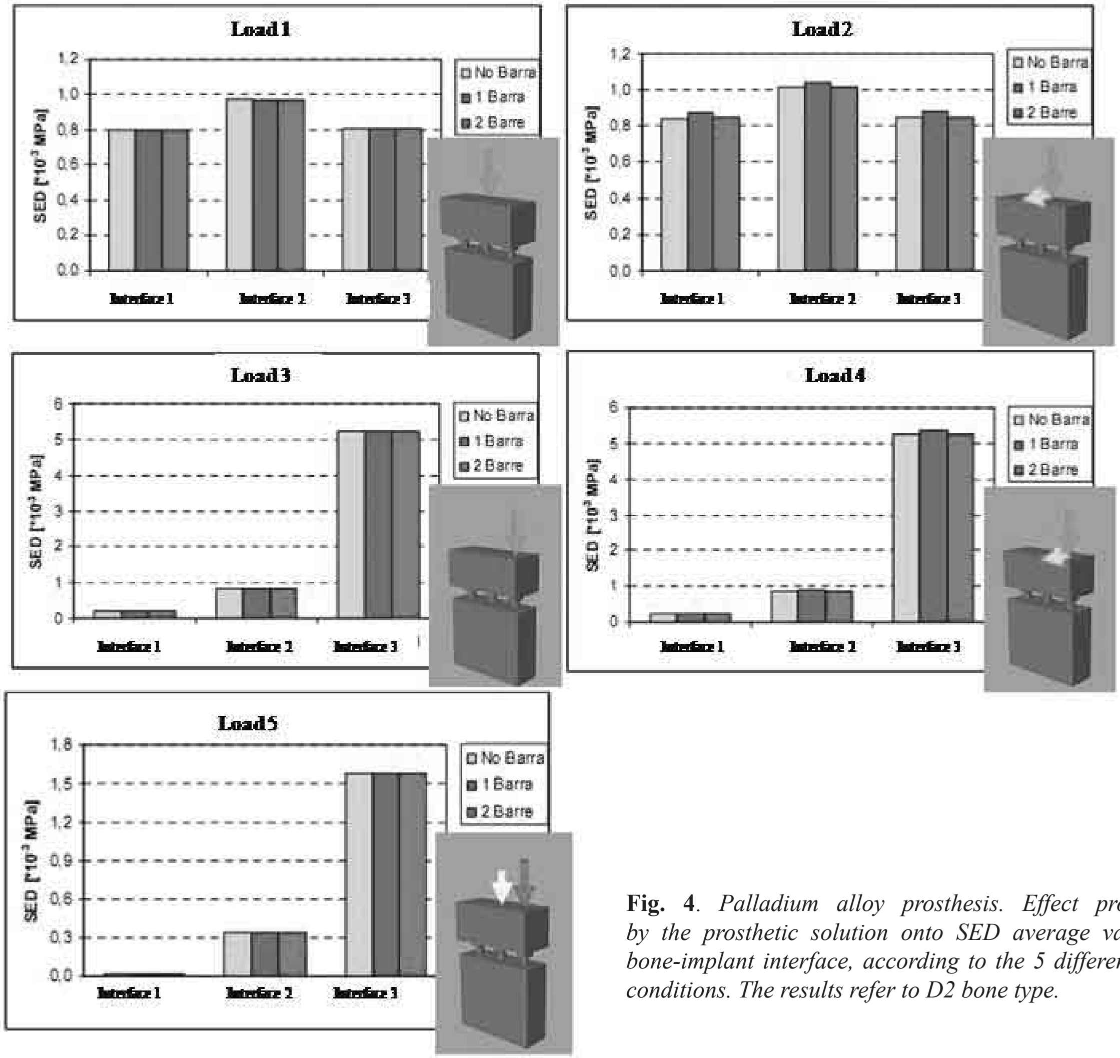


Fig. 4. *Palladium alloy prosthesis. Effect produced by the prosthetic solution onto SED average value at bone-implant interface, according to the 5 different load conditions. The results refer to D2 bone type.*

implant that undergoes more load.

Fig. 5 shows the results concerning the prosthetic procedure devoid of bar; however, as shown in Fig. 4, the bar has only slight effect on the stress /strain at the bone-implant interface.

The results concerning D4 bone type show that - even in case of low-quality bone - the application of one, two or no bar does not produce remarkable variations in SED average values, as tested at the three bone-implant interfaces (data not shown; they are available on request).

Bone type effect

The results of "no bar applied" show that SED at bone-implant interface is higher when the bone quality is lower (D4 bone type). This is due to a larger deformation produced in a tissue worse in quality and consequently weaker. If SED should reach extreme values, bone fracture might occur (data not shown; they are available on request).

Likewise, the results of "1.5 mm diameter solder bar" show that – whatever the load condition is –stress at the bone-implant interface reaches higher values in low quality bone type (D4) (data not shown; they are available on request).

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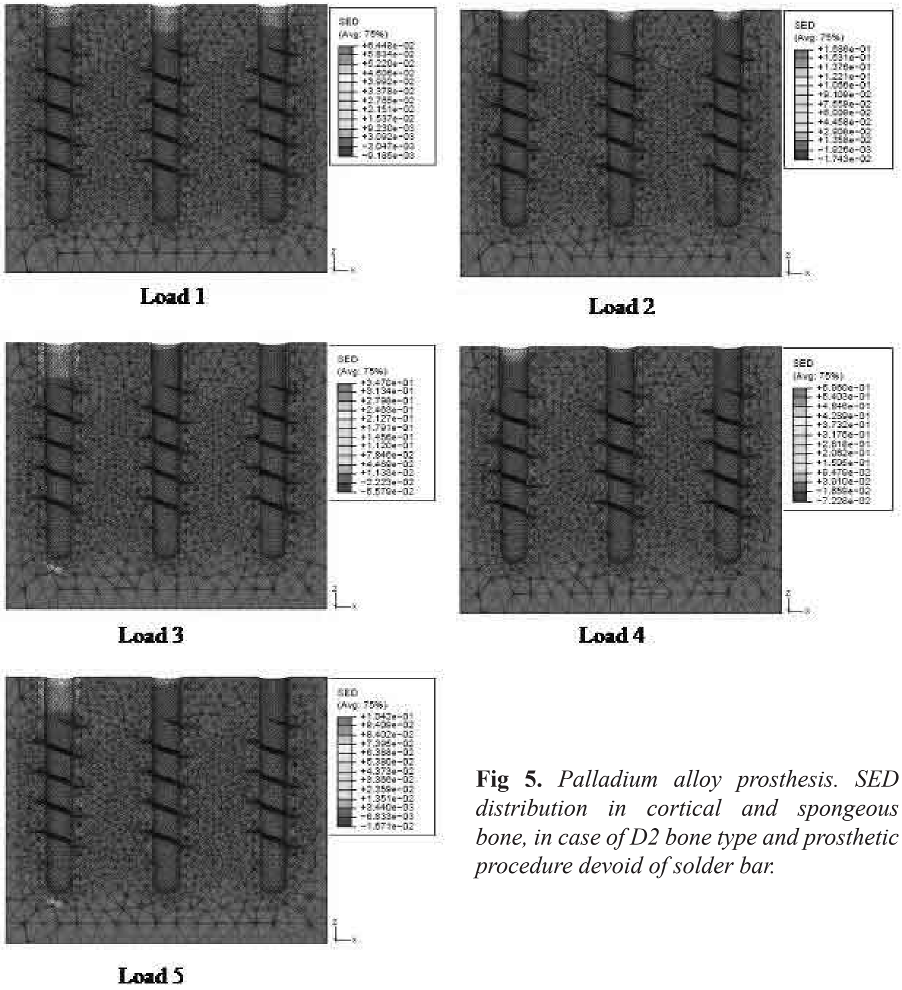
"Two 1.2 mm diameter solder bars" also report comparable results, as whatever the load condition is stress values keep higher when the bone quality is worse (D4 bone type) (data not shown; they are available on request).

Resin prosthesis

As for the analysis carried out on the palladium



Load 1

Load 2

Load 3

Load 4

Load 5

Fig 5. *Palladium alloy prosthesis. SED distribution in cortical and spongeous bone, in case of D2 bone type and prosthetic procedure devoid of solder bar.*

alloy prosthesis, the behavior of the resin prosthesis was analyzed by focusing on the effect on SED at bone-implant interface for each adopted procedure (none; one or two bars) with unvaried bone type and load condition.

The comparative analysis on the three implants in terms of SED average value at each bone-implant interface show that whatever the load condition is, the application of one or two stabilizing bars produces no relevant variation in SED average value at bone-implant interface, when compared with the use of prosthesis only (data not shown; they are available on request).

The results concerning D4 bone type show that even in case of low quality bone type the application of either one or two stabilizing bars does not produce relevant variations in SED average value at the three bone-implant interfaces.

In general, with equal load condition and prosthetic solution, SED average value at bone-implant interface is remarkably higher for D4 bone type than D2, due to a weaker consistency in the first type, in compliance with the results reported for the palladium alloy prosthesis.

Comparison metal /resin prosthesis

After assessing that a stabilizing bar does not produce relevant variations in the tensional status at the bone-implant interface for both metal and resin prostheses, a direct comparison between the two prosthetic materials becomes of primary interest.

The comparison between SED average values at D2 and D4 bone-implant interface for palladium alloy and resin prostheses, gives a distribution among the three implants more regular with the palladium alloy prosthesis. Under load conditions 1 and 2, with an external load applied at the center of the prosthesis, the metal prosthesis exerts an effective supporting action, as it distributes stress in quite a balanced way among the three implants; on the contrary, with the resin prosthesis most of the stress keeps being located around the central implant. By virtue of its stronger stiffness, the metal prosthesis manages to share stress among the three implants, thus achieving a sort of bonding effect, in such a way that is not reported about the resin prosthesis.

With the palladium alloy prosthesis stress distribution keeps being more regular and balanced, with either one large diametrically sized bar or two undersized bars. A crossed analysis of the data shows quite clearly that most of the bonding effect is due to the prosthesis strength instead of the welded bars. A metal prosthesis is in fact sturdy enough to contribute in bonding the implants, thus making the bars virtually unnecessary. On the contrary, prosthesis with weaker intrinsic stiffness such as the resin model could not create a bonding effect on the implants and the application of solder bars properly sized in terms of stiffness would be much of use.

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DISCUSSION

Analysis results have shown that a prosthesis which joins two or more implants produces in itself an important bonding effect. For such reason, once the prosthesis has been applied after the early post-operatory session, the prosthetic solution adopted (none; one or two welded titanium bars) will not affect the tensional status at the bone-implant interface. The application of bars is useful in an immediate post-implant period but it gets superfluous once the definitive prosthesis has been inserted. Therefore, there is no evidence of a specific benefit connected with the use of one diametrically oversized titanium bar set laterally as proposed by Dr Lorenzon, instead of two smaller bars set symmetrically to the implants. The bonding effect produced by the prosthesis depends on its stiffness, i.e. on its section and material; for example, the comparison between metal and resin prostheses shows the better distribution in stress/strain at the bone associated with the application of palladium alloy prosthesis, featured with a stronger stiffness than the resin unit. Unlike, SED values at the peri-implant bone prove to be affected by the bone type available in the implant site: the values rise as the osseous density lowers. However, even in case of low quality bone, the implant procedure adopted produces no meaningful variations in SED average value tested at the three bone-implant interfaces. SED distribution at bone-implant interface shows that tensions concentrate in the bone surrounding the implant necks: such region is in fact registered as critical in clinical general procedures, due to conoid resorption.

The results obtained show that when using a stiff prosthesis (metal is a better material, but resin is sufficiently effective) - whatever the bone type is - once osseointegration has completed, the prosthetic solution adopted does not affect the tensional status at the bone-implant interface. For its outstanding stiffness the metal prosthesis produces a bonding effect, which is stronger than the one exerted with the stabilizing bars made of a material similar in stiffness, though openly undersized in section. In conclusion, we can state that the use of a stiff definitive prosthesis (metal-porcelain) allows to remove the bar after 90 days' recovery, thus avoiding any cosmetic, hygienic and prosthetic contraindication.

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