Biomechanical dental implants comparison by means of numerical models and nuclear medicine

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Abstract

A review of recent literature revealed a very high success rate of implants used to support a mandibular overdenture as an alternative to the conventional removable dentistry. Today there are already several prosthetic solutions for the same clinical situations: in particular, the implant support can be different depending on the type of implants used and their layout. It is well known that the success or the failure of implants interfaced with bone depends, taking into account a favourable biological reaction, on the structural condition of the biomechanical system constituted by the bone structure and the implant. Knowledge of the strain/stress pattern can allow one to establish if bone maintenance, resorption or addition is more likely to take place.

In this work two different kinds of implant supports for overdenture retention were compared by means of FEM: they differed in the number of implants, their dimension, their location inside the mandible and, finally, in the presence/absence of a beam connecting all implants and making them all linked.

Clinical follow-up was assessed by means of technetium 99m-MDP scintigraphy. The obtained results agree with the clinical experience.
Keywords: dental implants, biomechanics, bone remodelling, FEM, nuclear medicine, bone scintigraphy.

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1 Introduction

The implant-supported prosthesis is an alternative to the conventional removable dentistry: while conventional denture may meet the needs of many patients, others require more retention, stability, function and aesthetics. A review of recent literature [1] revealed very high success rate of implants used to support a mandibular overdenture; for such a reason their use will become more and more widespread. Today there are already several prosthetic solutions for same clinical situations: in particular, the implant support can be different depending on the type of implants used and their layout, fig. 1.

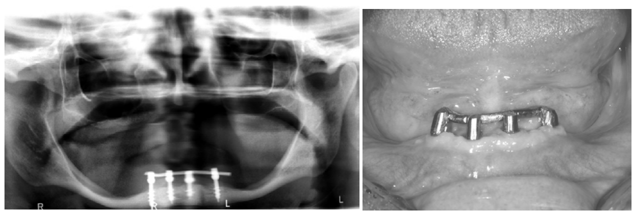


Figure 1: X-ray image (left) and picture (right) of an implant support solution.

The clinical comparison of different surgical treatments is difficult because, as a matter of fact, each patient has its own specific biomechanical situation and the scientific literature at the moment does not provide any clear directives to claims of alleged benefits of specific morphological characteristics of dental implants [2]. However, it is well known that the success or the failure of implants interfaced with bone (orthopaedic and dental implants) depends, counting on a favourable biological reaction, on the structural condition of the biomechanical system constituted by the bone structure and the implant [3, 4]. The knowledge of strain/stress pattern can allow to establish if bone maintenance, resorption or addition is more likely to take place [5]: Hoshaw *et al* [6] applied a dynamic axial tensile load for 500 cycles per day for five consecutive days to Brånemark implants inserted in the tibia of rabbit. The result was bone loss around the implant neck; a finite element analysis showed high strains in this region. Duyck *et al* [7] found crater-like bone defects as a result of a dynamic transversal load applied on Brånemark implants inserted bicortically in rabbit tibiae. The interpretation was that the bone loss had been caused by excessive stresses. Roberts *et al* [8] reported a high remodelling rate around the tops of implant threads. All these researches confirm that the analysis of stress pattern can give important indications for the choice of the kind of implant to be used.

The biomechanical system to analyse is complex because of the presence of different structures (compact bone, cancellous bone, gum, implant, prosthesis), which present complex geometry and different mechanical properties. For this reason, it is difficult to evaluate load transmission from the teeth to the bone intuitively, and Finite Element Method (FEM) is a necessary tool for comparative evaluations, allowing the simulation of different surgical treatments on the same bone situation.

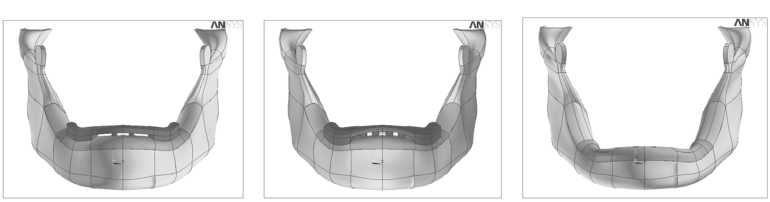
In particular, in this work, two different kinds of implant supports for overdenture retention were compared by means of FEM: they differed for the number of implants, for their dimension, for their location inside the mandible and, at last, for the presence/absence of a beam connecting all implants and making them all linked.

The numerical results were validated on the basis of the clinical outcome of 12 patients, whose oral tissue was rehabilitated by means of different kinds of dental implants; their follow-up was assessed through bone technetium 99m-MDP scintigraphy, a specific technique of nuclear medicine. Bone scintigraphy is a very sensitive method for the detection of the osteoblastic activity of the skeleton. The technique consists in imaging the uptake of bone-seeking radiopharmaceuticals, in the mineral component of bone as well as in the organic matrix; in particular, technetium-99m labelled diphosphonates are used [9]. Several recent medical reports have focused their attention on the possible application of skeletal scintigraphy imaging to odontostomatology [10–16].

2 Materials and methods

The first solution for overdenture retention will be called 'traditional' in the following and simulates the insertion of two Brånemark implants, parallel to each other, in the chin area. A resinous saddle is the basis for the prosthesis and is linked to these implants, fig. 2a. The second solution will be called 'modified' in the following and simulates the insertion of four screwed implants, anchored to the chin area with bi-cortical fixation. These implants are differently oriented and are connected to each other by a metallic wire, soldered by means of a syncrystallization process. The acrylic saddle used as a base for the prosthesis is attached to this metal wire. A plastic layer is placed between the wire and the saddle and works as a damper, fig. 2b.

These two solutions were applied to two different types of mandibles: the first one, called 'normal', has a physiological shape, while the second one, called 'resorbed', shows a remarkable resorption, as often encountered in the clinical practice, fig. 2c.



a) **b)** **c)**

Figure 2: FE models of a) a 'normal' mandible with a 'traditional' implant support design, b) a 'normal' mandible with a 'modified' implant support design, c) a 'resorbed' mandible.

Finally, four different numerical models were created: both ‘normal’ and ‘resorbed’ mandibles were considered with both kinds of implant support for overdenture retention.

Perfect osteointegration was simulated (secondary stability). The numerical models consisted of approximately 33000 4-node tetrahedra. Modeled materials are listed in table 1, while mechanical properties agree with data found in the literature [17, 18].

Table 1: Mechanical properties of materials.

Material	Young’s modulus [MPa]	Poisson’s ratio
Cortical bone	13000	0.3
Spongious bone	300	0.3
Gum	20	0.3
Titanium	100000	0.3
Resin	2000	0.4
Damping layer	500	0.4

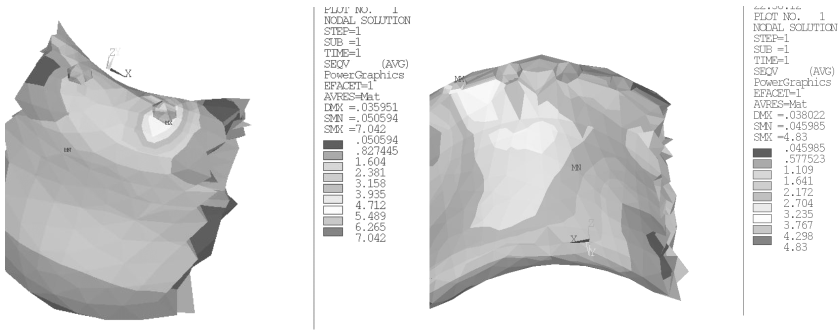
All models were asymmetrically loaded in correspondence of the second pre-molar. Distributed loads were applied, simulating the contact with the corresponding upper tooth; the vertical component of the load was equal to 50 N and the distal-mesial component was equal to 50 N [7]. Constrains simulated the action of muscles during mastication.

Numerical results were validated against the clinical outcome of twelve patients, aged 42-65 years, randomly chosen, informed and consenting; these patients were injected with 370MBq of Tc-99m-MDP and scanned 3 hours later by a gamma-camera in order to assess the isotope uptake by the mandible. The physical half-life of the agent is 6 hours and about 50% of the administered dose is absorbed by the osseous tissues within 2-3 hours of injection; the remainder is very rapidly excreted by the kidneys. The absolute count for each gamma-camera survey is dependent upon the individual bone mass, time passed from the administration, and the rate of metabolic activity; these variables changed from patient to patient. Therefore, the results of each scan were standardised to produce a “bone scan index”: the scan count at the peri-implant tissue is referred to the skull and the contralateral non-treated side of the mandible. Seven patients were rehabilitated with a traditional dental support design, while five patients were rehabilitated with needle implants, connected to each other by means of a metallic wire through a syncrystallization process. The follow-ups of all the patients ranged between 18-36 months.

3 Results and discussion

The main attention of this analysis was focused on stress/strain pattern in cortical and trabecular bone in order to assess if the structural condition was favourable to bone remodelling. First of all, von Mises stress were considered to highlight the most stressed areas, after a more detailed analysis was carried on to assess the orientation of principal stresses in that area.

The analysis of von Mises stresses in cortical bone pointed out that the peak stress occurred in correspondence of the implant located nearest to the applied load, for both implant support solutions, fig. 3a, b. The peak stress was located at the implant insertion into cortical bone, on the distal side. The same pattern was observed in the case of the atrophic mandible, but the peak stress had slightly decreased, fig. 4.



a) **b)**

Figure 3: von Mises stresses in the cortical bone of a ‘normal’ mandible: a) 'traditional' implant support design, b) ‘modified’ implant support design. Stress values are in MPa.

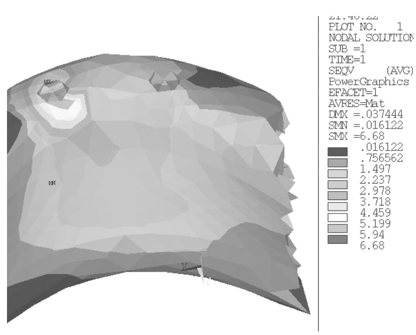


Figure 4: von Mises stresses in the cortical bone: 'traditional' implant support design applied on a ‘resorbed’ mandible. Stress values are in MPa.

A more detailed stress analysis pointed out that the peak stress is due to a notch effect: stress field is typically three-axial, the stressed area is very small and corresponds to the clinical evidence of conical resorption [6]. The ‘resorbed’ mandible has a smaller cross section but stresses remain nearly the same as the ‘normal’ mandible because, in both cases, only a small portion of the total bone-implant interface area carries the external load. Furthermore, the ‘resorbed’ mandible is more flexible and therefore notch intensity factor is lower.

The analysis showed also that the most influent component of the force was that one along y (distal-mesial) direction because the application point of the force was nearly aligned with one of the constrain points, along the z (vertical) direction.

However, the comparison between the ‘normal’ and ‘resorbed’ mandible results was biased by the assumption that bone quality was the same in both cases. Having assessed the influence of pure morphological variation as done in this work, further study should be performed taking advantage of recent works [19] describing how the mechanical properties of mandibular bone (Young’s modulus and ultimate stress, mainly) vary as a consequence of bone resorption.

On the whole, the ‘modified’ implant design produced lower stresses than the ‘traditional’ one (-34% of von Mises stress).

This result can be explained on the basis of the following observations: first, the load is distributed on a larger number of implants, second, the notch effect is reduced whenever more than one discontinuities are present: stress distribution is more uniform, even if the average stress level raises.

The numerical finding is corroborated by the clinical experience of the third author and by radiographic findings where larger alveolar bone losses (typical resorbed cones) are visible in correspondence of Brånemark implant insertion into the bone. Other works in literature agree with this assertion [20].

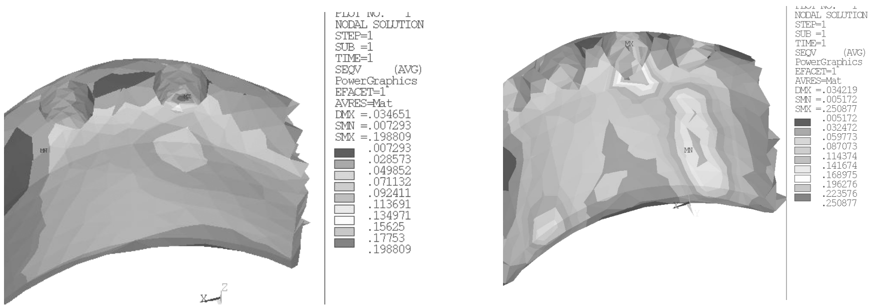
A more detailed analysis was performed in order to assess the structural importance of the metallic wire connecting all implants in the ‘modified’ solution; for this aim a hypothetical model without wire was developed. The numerical analysis demonstrated that the removal of a 2 mm diameter wire, produces a peak stress 5% higher: the reduction of implant-bone system stiffness was moderate because, having considered secondary stability, the implants were linked to each other by means of cortical bone which has a lower Young’s modulus than the metallic wire, but shows a definitively more favourable geometry due to its larger dimensions.

Different results should be expected if primary stability had been studied, because the implant would not be osteointegrated yet and consequently the constrain given by the cortical bone would rely only on contact forces.

The stresses in the trabecular bone for ‘traditional’ implant support design pointed out how the most stressed area, this time, was located in correspondence of the distal tip of the implant, opposite to the loaded area, fig. 5a; these stresses could be disregarded for two main reasons: their magnitude was low [19] and their location was far away from the proximal implant area which is the most critical for what concern bone remodelling.

In the case of the ‘modified’ implant, the most stressed area was next to the implant insertion, fig. 5b and the location changed moving form the ‘normal’ mandible to the atrophic one, fig. 6; on the whole, stresses were quite well distributed on the entire implant area and they never reached critical values [19].

As regards bone scintigraphy, images like figure 7 were analysed: the level of osteoblastic activity in the mandible results in different grey levels. A metabolic activity of the peri-implant bone tissue was evident in all five out of the seven cases where the oral tissues rehabilitation was performed with traditional implants; on the contrary, no metabolic activity of the peri-implant bone tissue was evident for all five patients, rehabilitated with needle implants connected to each other by means of a metallic wire.



a) **b)**

Figure 5: von Mises stresses in the trabecular bone of a ‘normal’ mandible: a) 'traditional' implant support design, b) ‘modified’ implant support design. Stress values are in MPa.

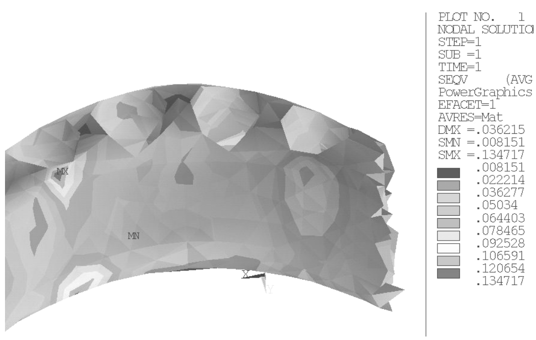


Figure 6: von Mises stresses in the trabecular bone of a ‘resorbed’ mandible with a ‘modified’ implant support design. Stress values are in MPa.

Bone scans are able to show reactive modifications in osteoblastic activity that would not appear on radiographic images, but they do not show morphologic changes due to their low resolution. In detail, bone scintigraphy may be positive if the increase in the osteoblastic activity is approximately 10% above normal level [21], while conventional radiologic techniques require an alteration of the bone mineral content equal to 30 to 50% in order to detect bony changes. Besides, morphological alterations are usually the final result of a biochemical process that has remained undetected until the development of physical symptoms.

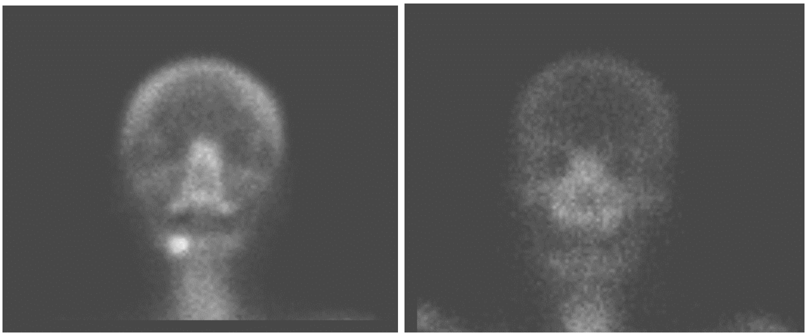


Figure 7: Bone scintigraphy images: evident peri-implant bone metabolic activity (left) and absence of such activity (right).

4 Conclusions

The purpose of this study was to compare the effect of different implant support designs for overdenture retention in order to identify the solution that produces a better biomechanical behaviour for the bone-implant system. This comparison was performed numerically, by means of a three-dimensional finite element models, and it was validated clinically by means of a nuclear medicine technique.

The implant support consisting of four bicortical screws resulted in a peak principal stress 34% lower than the implant support consisting of two Brånemark implants.

The difference between the structural behaviour of implanted 'resorbed' and 'normal' mandibles was negligible for the considered load, however ultimate stress was different between these two situations and further studies should take into account the different mechanical properties of the bone between a 'normal' and a 'resorbed' mandible.

The application of a metal wire which links all bi-cortical screws produced a stress reduction equal to about 5%, but also the primary stability should be investigated because, in this case, the action of the metallic wire which limits implant bending would be surely emphasised.

Bone scintigraphy carried out on a restricted number of patients has demonstrated that osteoblastic activity has taken place in the majority of cases where traditional dental implants had been implanted, even in asymptomatic patients. On the contrary, no osteoblastic activity has been visualised in all cases where innovative needle implants were implanted, connected to each other by means of a metallic wire.

Finally, the finite element method has been validated and consequently demonstrated to be suitable for simulating complex biomechanical systems in the maxillofacial area; on the other side, bone scintigraphy has proved to be a valuable test to follow up the peri-implant bone tissue and to assess the ongoing bone remodelling activity.

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