J Stomatol Oral Maxillofac Surg 124 (2023) 101463

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Original Article

Is All-on-four effective in case of partial mandibular resection? A 3D finite element study

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A R T I C L E I N F O

Article History:
Received 6 March 2023
Accepted 1 April 2023
Available online 5 April 2023

Keywords:
Prosthesis implantation
Biomechanics
Mechanical stress

A B S T R A C T

Introduction: The aim of the work is to analyze stress distribution on 3D Finite Element (FE) models at bone, implant, and framework level of different designs for fixed implant-supported prostheses in completely edentulous patients, comparing results on whole and partially resected mandibles.
Materials and methods: 3D anisotropic FE models of a whole and of a partially resected mandible were created using a TC scan of a cadaver's totally edentulous mandible. Two types of totally implant-supported rehabilitation were simulated, with four implants: parallel fixtures on whole mandible and on resected mandible, All-on-four-configured fixtures on whole mandible and on partially resected mandible. A superstructure comprising only metal components of a prosthetic framework were added, while stress distribution and its maximum values were analyzed at bone, implant, and superstructure level.
Results: The results highlight that:
(1) implant stresses are greater on the whole mandible than on the resected one;
(2) framework and cancellous-bone stresses are comparable in all cases;
(3) on the resected mandible, maximum stress levels at the cortical-bone/implant interface are higher than in whole-mandible rehabilitation. The opposite applies for maximum stresses on external cortical bone, measured radially with respect to the implant from the point of maximum stress at the interface.
Discussion: On the resected mandible, All-on-four configuration proved biomechanically superior to parallel implants considering radial stresses on implants and cortical bone. Still, maximum stresses increase at the bone/implant interface. A design with four parallel implants minimizes the stress on a resected mandible while, on the whole mandible, the All-on-four rehabilitation proves superior at all levels (bone, implant, and framework).

1. Introduction

1.1. General context

Mandibular resection is performed mainly in the case of ablations of advanced intraoral squamous carcinomas that spread to the mandible. Additionally, less frequent grounds for this surgical procedure are benign tumors, primitive endosseous malignant tumors, traumas (automobile accidents, wounds), infections, and osteoradionecrosis [1]. The loss of bone and teeth brings functional difficulties (e.g., mastication and speech) and esthetic consequences with the serious alteration of facial contours. These problems are accentuated as the remaining segments of the mandible are subjected to a muscular dislocation that displaces them towards the area left empty, leading to a serious form of malocclusion. Since nervous tissue is also removed, the proprioceptive sensitivity of the lower lip and, sometimes, of the homolateral hemilingua is reduced or lost, thus aggravating speech and salivation problems. Moreover, mouth opening is often severely reduced [1,2].

Osseointegrated implants in the dental rehabilitation of these patients are fundamental because they are highly predictable means of providing sufficiently stable and retentive prostheses where a profoundly altered anatomy rarely permits adequate results through conventional prosthetic rehabilitation [1,3,4]. In particular, when patients have undergone post-operative radiation treatment, a fixed totally implant-supported prosthesis is preferable to an overdenture on implants to prevent the friction of the prosthetic flange against the delicate tissues of these patients from provoking ulcerations, also leading to septic osteonecrosis [3].

1.2. Problem

In clinical practice, there are partially or wholly edentulous patients who have not undergone a surgical reconstruction in the

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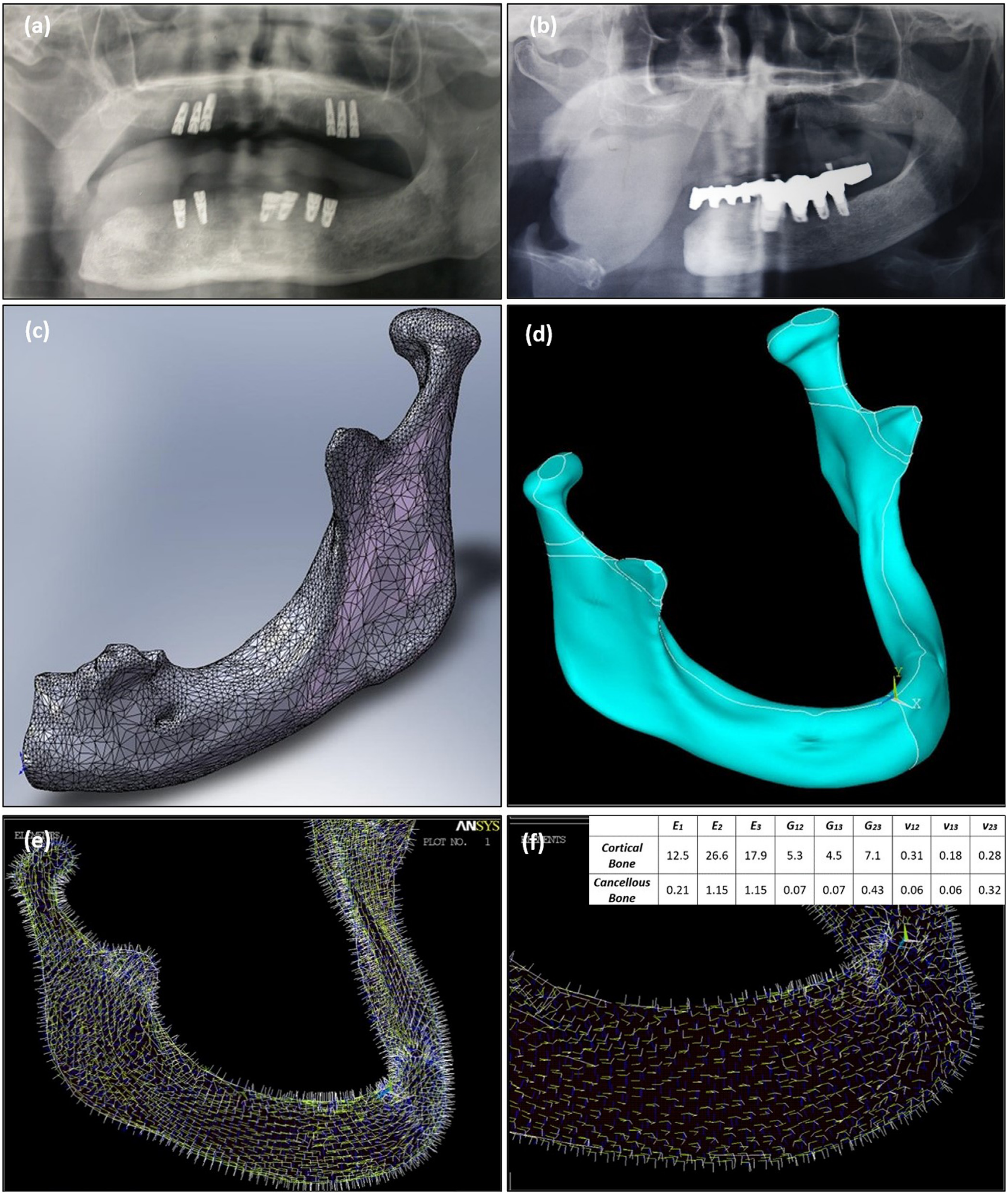
https://doi.org/10.1016/j.jormas.2023.101463

wake of a mandibular resection, even a narrow one (Fig. 1a). This is due either to an advanced age, to serious concomitant systemic pathologies, or to pronounced vascular problems [4]. In the prosthetic rehabilitation of the full lower arch, there is the problem of very long prosthetic cantilevers (Fig. 1b). The use of at least four osseointegrated implants has been suggested for the rehabilitation of



	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{13}	ν_{23}
Cortical Bone	12.5	26.6	17.9	5.3	4.5	7.1	0.31	0.18	0.28
Cancellous Bone	0.21	1.15	1.15	0.07	0.07	0.43	0.06	0.06	0.32

Fig. 1. Patient with limited mandibular resection who has not undergone surgical reconstruction (a) and long distal cantilever in a fixed totally implant-supported prosthesis in a patient with mandibular resection where no surgical reconstruction has been performed (b); faceted mandible (c) and model in ANSYS environment (d), which has been smoothed using Solid-Works software, together with a view (e) and related zoom (f) of the local coordinate frames employed for bone elastic properties, one for each element. The table in (f) reports the bone elastic properties, where E_i represents Young's modulus (GPa), G_{ij} the shear modulus (GPa), ν_{ij} the Poisson ratio: for cortical bone, the directions are sequentially radial, tangential, and axial, while for cancellous bone the directions are inferior-superior (the transversally isotropic simmetry axis with the lowest Young's modulus), medial-lateral, and anterior-posterior.

patients with a resected mandible, and especially those who have undergone post-operative radiation treatment. The rationale for this option lies in the maximal prosthetic support and the adequate protection of soft tissues [4]. In a whole mandible, tilted terminal implants characteristic of the All-on-four method permit a relatively favorable biomechanical situation that shortens of distal prosthetic cantilevers [5]; the same could be applied to the rehabilitation of a resected mandible to resolve the problem of excessive cantilever length.

1.3. Aim of the article

The study aims at evaluating, by 3D Finite Element (FE) analyses, patterns of stress distribution on bone (cortical and cancellous), implants and framework in two different designs for the implant-supported rehabilitation of edentulous patients who have undergone mandibular resection but no subsequent surgical reconstruction:

(1) Conventional fixed-detachable prosthesis with four parallel and equidistant interforaminal implants.

(2) All-on-four prosthesis, with the two terminal fixture distally tilted at a 34° angle.

The results were then compared with FE simulations on the same types of rehabilitation in patients with whole mandibles.

The goal is to compare these two designs for implant-supported prostheses on resected mandibles to observe which one is better in biomechanical terms, then to compare them with the simulations on a whole mandible to determine how much the integrity or non-integrity of the mandible affects the pattern of stress distribution across bone, implant, and prosthetic superstructure.

2. Materials and methods

2.1. Modelling the mandible

The mandible of a cadaver was used as the anatomical basis for the 3D models, analyzed by a volumetric TC scan from a Siemens Somatom Plus 4 spiral tomograph. The TC scan was performed with 1 mm-thick slices and then processed using Mimics version 10.01 to obtain two 3D masks simulating cancellous and cortical bone (mean thickness 1.5 mm). These were then saved in IGS electronic format and transferred to SolidWorks version 2020, with which all the faceting of the mandibular surface was smoothed out (Fig. 1c and d). Half of the obtained mandible was then divided into three parts: the hemimandibular body (including the ramus), the condyle and the coronoid process.

The surfaces thus obtained were uploaded into the ANSYS v11 software for FE analysis. The elastic properties of the bone were set as anisotropic, thus distinguishing the elastic behavior of cortical bone from that of cancellous bone. Cortical bone was considered as orthotropic material [6], cancellous bone transversally isotropic [7] (Fig. 1f). The characteristic directions represented for cortical bone were radial, tangential, and longitudinal, varying from point to point across the mandible surface. Conversely, for the cancellous bone only the radial direction was considered, as the tangential and longitudinal elastic coefficient are equal [8] (Fig. 1e and f). Finally, as regards the boundary conditions, the mandible was "constrained" in space by fixing two surfaces positioned on the condyle and on the coronoid process. The mesh of the mandible resulted in 1.5 mm elements in the interforaminal region of the cortical bone and of 2 mm elements in the remaining parts of the mandible (lateral/posterior region of the cortical bone and interforaminal and lateral/posterior regions of the cancellous bone). The mesh was more densely rendered in the symphyseal and premolar areas, the most significant for this kind of study. The complete mandibular model comprises about 143,000 tetrahedral elements with about 207,000 nodes.

2.2. Simulating the patient with mandibular resection

To mimic mandibular resection, the model described above was cut on the right side on a plane perpendicular to the mandibular body and situated distally with respect to the right mental foramen at 3 mm (Fig. 2a). The type-H defect sparing the ipsilateral mental foramen was considered according to the classification of Boyd et al. of 1993 [9].

2.3. Modelling the implants

In modelling the implants, a Straumann Regular Neck transgingival implant was referenced with a diameter and an endosseous length of 4.1 mm and 11.45 mm, respectively, and with a platform and a total length of 4.8 mm and 15.3 mm, respectively. A single implant was modelled as a discrete volume to be replicated as needed. The implant's threads or internal configuration were not modelled for simplicity (it does not change stress distribution patterns in FE analysis [10]). The implant was also modelled seamlessly with respect to the bone surface, simulating 100% osseointegration (Fig. 2b). The material utilized in modelling the implant was an isotropic, homogeneous, and linearly elastic titanium (Young modulus 103.44 GPa, Poisson ratio 0.35) [11]. The characteristic dimension of the implants' elements was circa 1 mm, but in the most relevant areas (e.g., the distal bone-implant interface) the mesh was refined to 0.5 mm. The complete implant model comprises about 21,000 tetrahedral elements and about 31,000 nodes per fixture.

2.4. Modelling the structure

Only the metal part of the prosthetic framework was modelled and in a schematic form, i.e., as a regular solid with a 6×6 mm^2 section whose semicircular form followed the curve of the mandible's crest. In the configurations with parallel implants, a distal cantilever 20 mm long on either side was simulated, whereas in the configuration with tilted implants the length of the cantilever was reduced to 13.6 mm in proportion to the 34° angle of the implants.

To simplify modelling, the structure was conceived as firmly bonded to the implants; neither the screws nor the corresponding perforations of the structure were rendered (Fig. 2c). The complete model comprises 7200 tetrahedral elements and about 12,000 nodes.

2.5. Finite element analysis

The elements described above were combined to create the four FE models in Fig. 2d:

- fixed prosthesis supported by 4 parallel and equidistant interforaminal implants on whole mandible (**4PIn**);
- fixed prosthesis supported by interforaminal implants in All-on-four configuration, with the two posterior implants tilted distally at a 34° angle, on whole mandible (**AO4n**);
- fixed prosthesis supported by 4 parallel and equidistant interforaminal implants on resected mandible (**4PIr**);
- fixed prosthesis supported by interforaminal implants in All-on-four configuration, with the two distal implants tilted distally at a 34° angle, on resected mandible (**AO4r**).

In the 4PI simulations the distance between fixtures was 12 mm. In the AO4 simulations the mesial implants are 12 mm apart and, to either side, 15 mm separate the mesial and distal implants.

Each implant-supported design was subjected to a static load of 200 N applied to a point at the end of the right distal cantilever on a

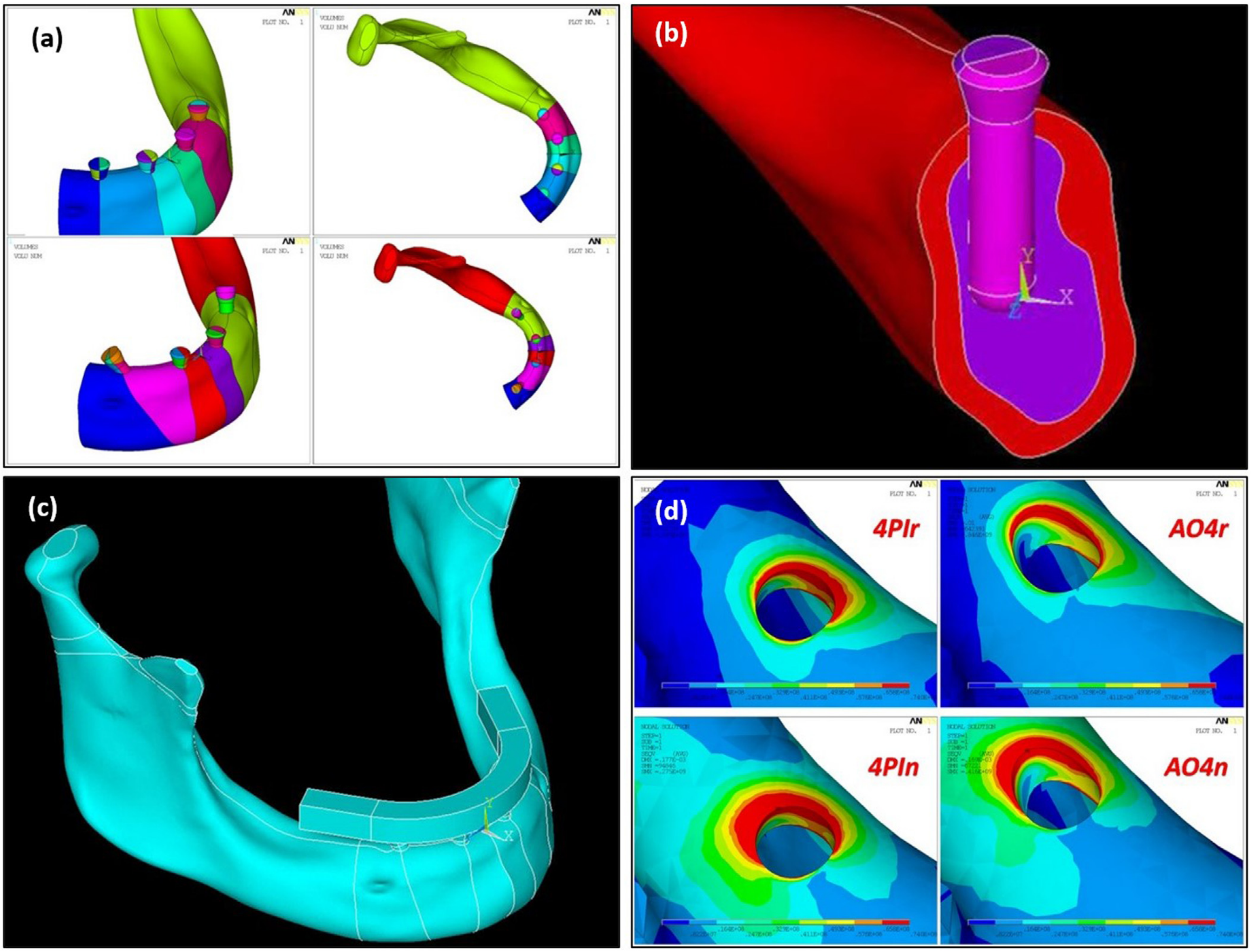


Fig. 2. Simulations of patients with mandibular resection (a) and example of the interface between implant, cortical bone in red, and cancellous bone in purple, where the implant is "bonded" to bone assuming a 100% osseointegration; example of a complete FEM with mandible, implants and prosthetic superstructure (c) and representation of the four types of rehabilitation analyzed by means of the FEA (d).

lingual trajectory 25° from the vertical plane and 60° from the sagittal median plane. An inclined force was adopted to approximate a real masticatory load, since a force of this scale is the maximum masticatory load generated by patients with a fixed-detachable prosthesis that occludes with a totally removable prosthesis, a situation commonly encountered in clinical practice; however, loads on patients with resected mandibles are actually smaller [12]. The masticatory load is applied with a single vector at a point, even though it should be evenly distributed along the whole arch [13]. The solution is chosen to represent the worst possible stress condition, i.e., a load exerted at the end of the 20 mm-long distal cantilever (slightly longer than the 15 mm suggested in the literature [4]).

The computer used to perform the analyses is an Intel Core 2 Quad CPU 2.40 GHz with 3 GB of RAM and the results are expressed by Von Mises equivalent stresses. These were considered even for the anisotropic portion of the FE model because they provided a valid indication of the stress level at a given point within the material. FE models were created with three types of mesh, differing in the dimensions of their elements at the bone-implant interface: 1 mm (coarse mesh), 0.5 mm (medium mesh), and 0.25 mm (fine mesh). These were then compared through convergence tests to minimize the "singularity problem" that reduces interpretability of the FE results [14].

3. Results

3.1. Stress on cortical bone

Based on the results of the performed convergence tests of stress levels in relation to the distance from the maximum values encountered both at the bone-implant interface and radially, at the outer cortical bone the following reference values were used:

- for the stress at the bone-implant interface, that of the same stress detected on a generator of a cylindrical interface of the same sort at a distance of a half a millimeter from the point of maximum stress;
- for the stress at the outer cortical bone exerted radially with respect to the implant site, at 1.3 mm from the point of maximum stress at the level of the more distal implant on the loaded side.

Fig. 3a presents the distribution patterns of both radial and bone-implant-interface stresses at the cortical bone at the level of the right terminal implant and for all the configurations analyzed, this being the closest area to the point loaded (subjected to the highest concentration of stress [15]). Stresses mainly distributed

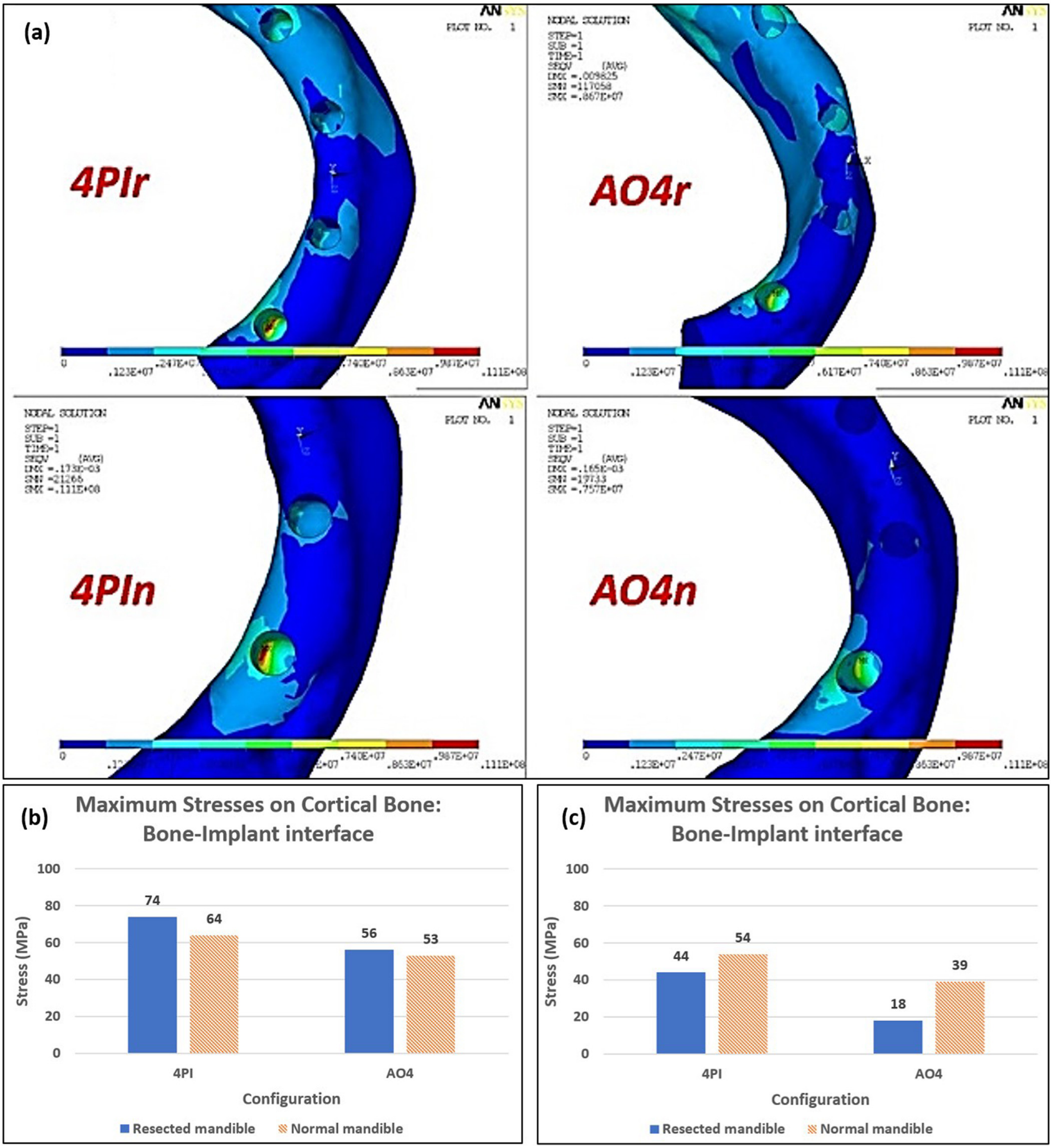


Fig. 3. Pattern of stress distribution at the level of the mandibular cortical bone in each of the four implant configurations (a); maximum stresses on cortical bone at the bone-implant interface (b) and maximum stresses on cortical bone at the external radial bone (c).

lingually on the resected mandible, but more distally on the whole mandible. In each case, stress most strongly concentrated in the most occlusal portion of the bone—implant interface. The AO4 configuration brought a reduction in stresses at the cortical bone level with respect to the alternative with parallel implants (Fig. 3b and c), above all radially at the level of the outer bone. At this level, the indicated stresses were greater in the simulations on the normal mandible than on the resected mandible (Fig. 3c).

3.2. Stress on cancellous bone

In each of the analyzed cases, the maximum stress on the cancellous bone exerted on the lingual face of the apical portion of the bone—implant interface was derived (Fig. 4). The maximum stresses on cancellous bone for the four implants were:

- 4PIn: 11.1 MPa
- 4PIr: 11.0 MPa
- AO4n: 7.6 MPa
- AO4r: 8.7 MPa

Comparison showed that the values for the whole and the resected mandible were essentially identical, diminishing slightly with the AO4 configurations. Comparing these with the results obtained for the cortical bone, it could be noted that they were substantially lower (Fig. 3b and c).

3.3. Stress on implants

Comparison of the images for the FE analysis of the implants highlighted that in all the performed simulations the maximum stress appeared at the lingual side of the neck of the terminal implant of the loaded side (Fig. 5a and b). As regarded the not loaded side, whereas the configurations on the whole mandible showed a considerable drop in the stress, those on the resected mandible exhibited a significant increment in the stress at the level of the neck of the terminal implant in the mesio-lingual direction. In the vestibular view (Fig. 5c), the AO4 configurations diminished stress concentration at the level of the implant neck. Fig. 5d compares the maximum stresses detected at the level of the implants: it could be noted that the AO4 configurations generally entailed lower stresses on the fixtures, which demonstrated to accumulate greater stress in rehabilitated whole mandibles rather than in rehabilitated resected mandibles.

3.4. Stress on prosthetic superstructure

Considering the stress at the upper part of the prosthetic framework, in all the performed simulations the peak stress levels were found in the premolar area of the loaded side, but in a slightly more distal position with the AO4 configurations. This also holds for the lower portion of the framework, with the point of maximum stress discerned between the disto-lingual edge of the neck of the more distal neck on the loaded side and the framework itself (Fig. 6a and b). Comparison of the obtained maximum stress values (Fig. 6c and d) showed that in both the lower and upper portions of the framework the stress concentration is reduced with the AO4 configurations compared to those on parallel implants, and on both the whole and resected mandibles. In Fig. 6a and b, the most distal portion of the right side of the structure exhibited a slight depression: this tool was adopted in the presentation of the results because this corresponded to the point at which the force was applied; had it been left, it would have constituted a “point of singularity” [14].

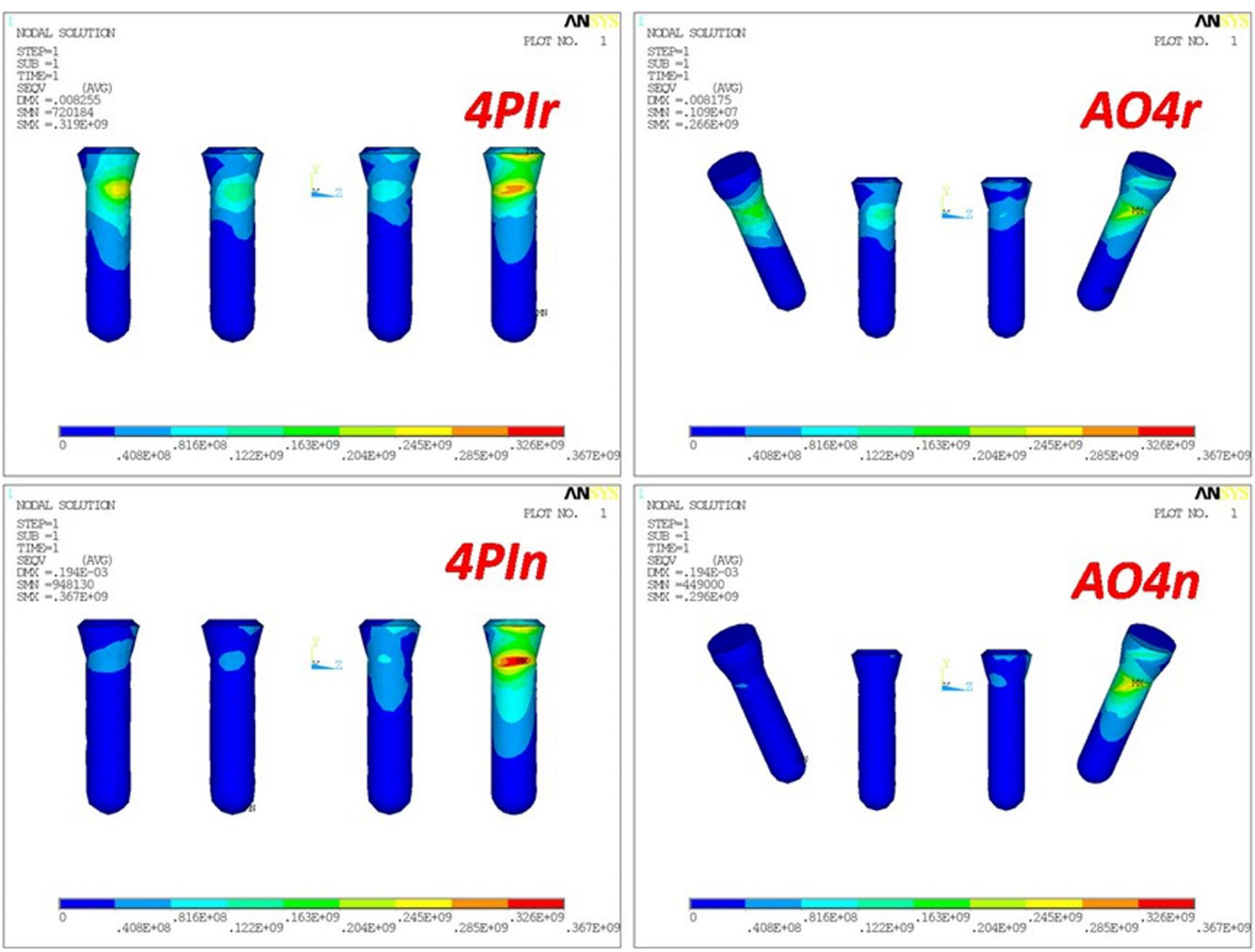


Fig. 4. Pattern of stress distribution at the level of the mandibular cancellous bone in each of the four implant configurations.

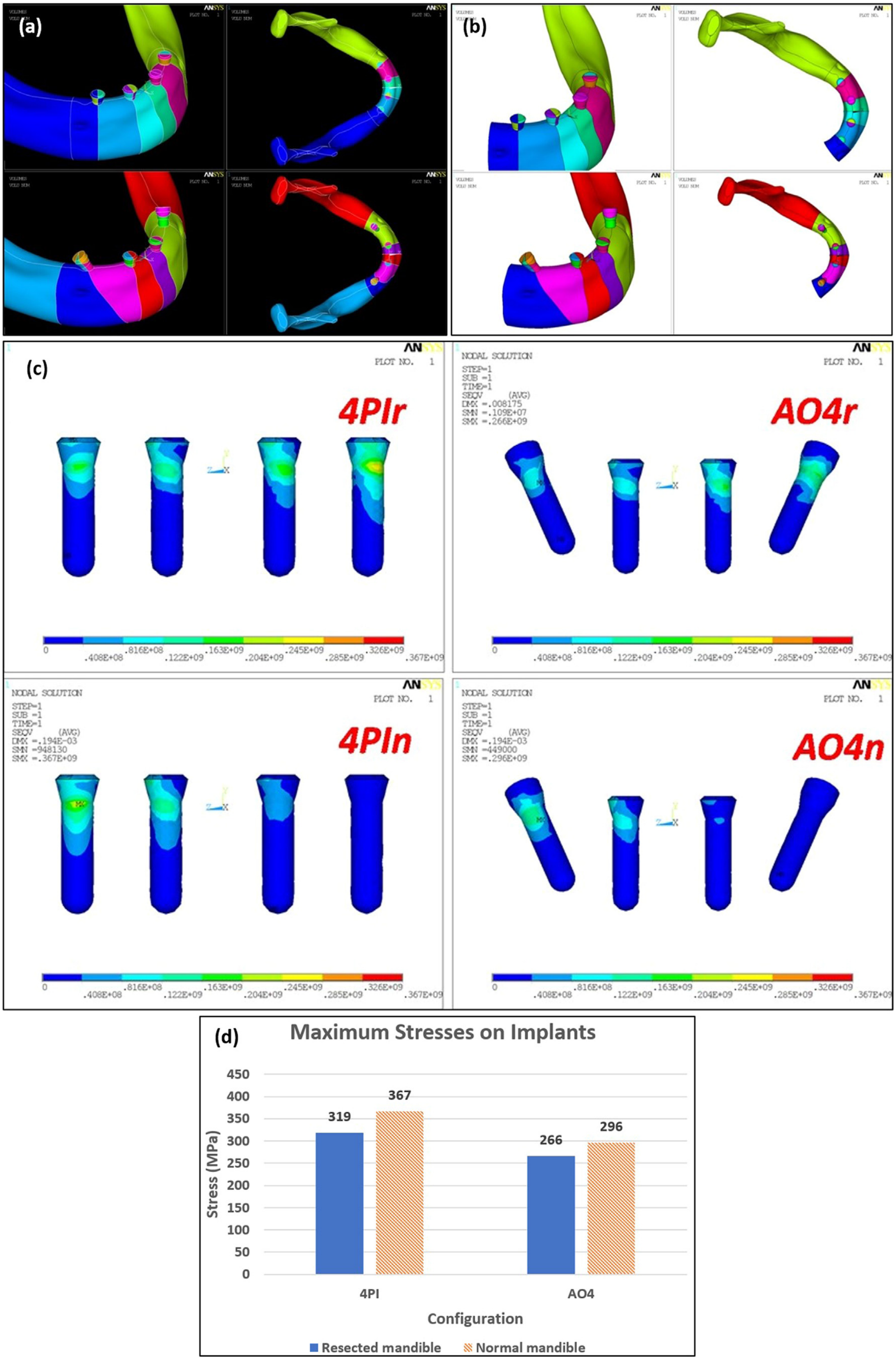


Fig. 5. Pattern of stress distribution at the level of fixtures in each of the four implant configurations from the lingual view (a-b) and the buccal view (c); maximum stresses on implants (d).

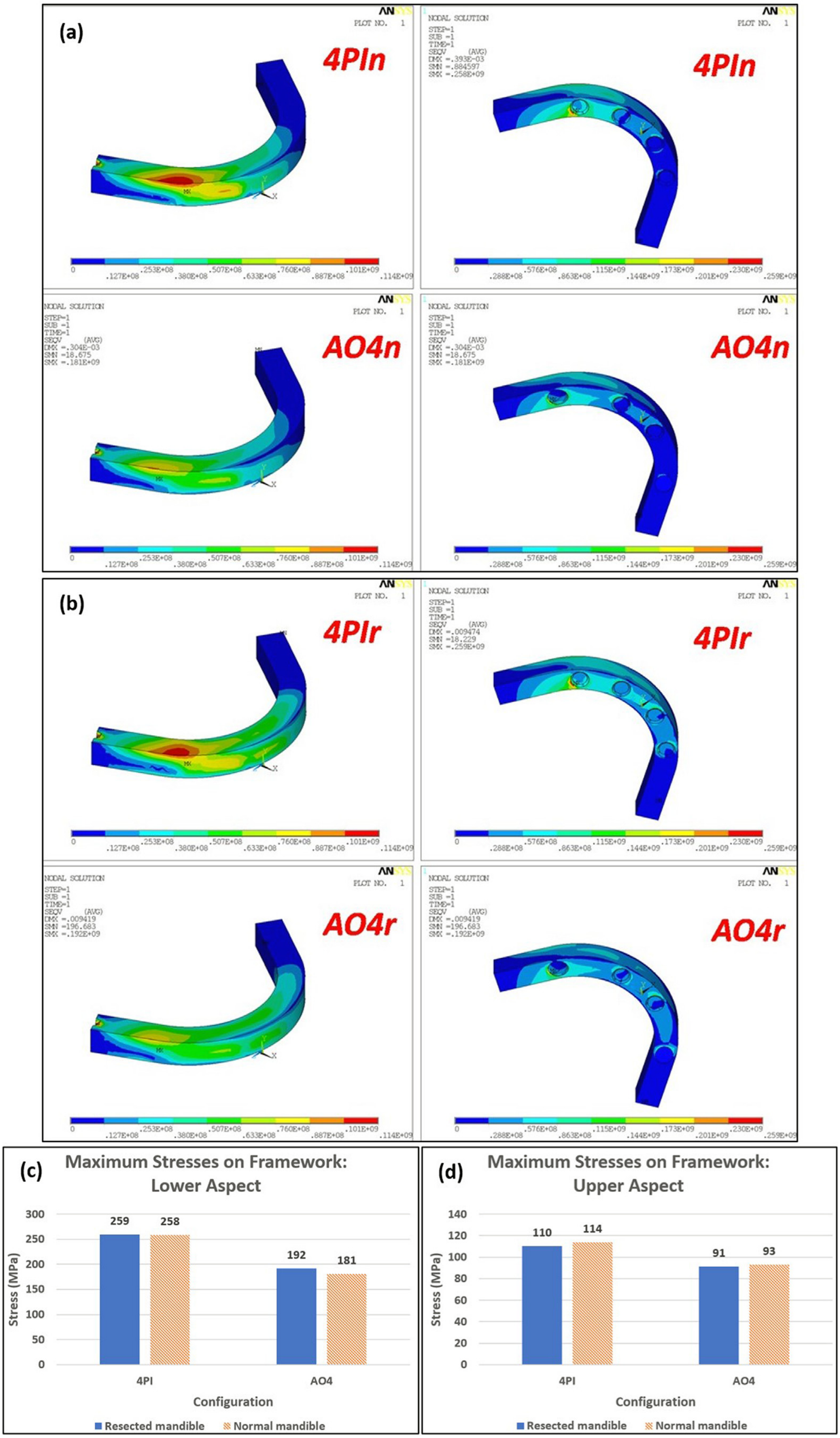


Fig. 6. Pattern of stress distribution at the level of the prosthetic framework in each of the four implant configurations, deriving from simulations on resected mandible (a) and simulations on the whole mandible (b); maximum stresses on the framework in the lower aspect (c) and in the upper aspect (d).

4. Discussion

4.1. State of the art in finite element analysis

Geometrical fidelity and a suitable characterization of the elasticity of the materials were considered as essential prerequisites for achieving an FEA capable of yielding reliable results [16]. Less recent studies on fixed-detachable prostheses should be considered inadequate from this standpoint, either because they used 1D [17] or 2D-3D FE models with schematic forms [13], with only that of van Zyl et al. had a 3D mandibular model with a geometry comparable to reality [18]; conversely, the most recent efforts gave more attention to this component of the FE modelling [5,11,19,20]. In the 1990s, Cowin et al. [21] showed that an error in the orientation of the axes of the principal stresses resulted from the modeling of the bone as isotropic. Recent studies further demonstrated that an FE analysis cannot disregard an anisotropic model in studying the elastic behavior of mandibular bone [19].

Only the 2009 work of Bonnet et al. closely approximated this study's modelling of the bone tissue, however considering significantly fewer specific local coordinate frames [19]. The models created in the present study provided a distinct coordinate frame for each element of the bone, making for a precise simulation of the generated stresses [19]. Regarding bone modelling, also representation of the trabeculation of the cancellous bone could have been interesting as in the work of Ohashi et al. of 2009, where it was applied to Beagle dogs [22]. Given that Ohashi did not provide the strength of the forces detected, incorporating the representation of the trabeculation here would have not changed the substance of the distribution of forces. To setup accurate FE models, technicians can also refer to the work of Vukicevic et al. of 2021 [23], comprehending a very detailed anisotropic 3D mandibular model freely available on an online repository. Additionally, various FE analyses concerned with patients with reconstructed mandibles could be found [24], whereas the present study has been the first to apply this analytical technique to persons with mandibular resection but who have not undergone surgical reconstruction.

The relatively rigid cortical component of the alveolar bone undergoes the greatest stress concentration (Fig. 3b and c), tallying with the data reported in literature [25]. At the level of the bone-implant interface, on the resected mandible (especially in the case of the parallel-implant prostheses) an increment in the stresses compared to its whole-bone counterpart was highlighted, whereas the exact contrary occurs at the external radial bone (Fig. 3c). This was probably caused by the absence of constraints in the resection-affected area. This factor may also be responsible for the lingual flow in the stress distribution pattern at the mandibular cortical bone in the simulations on the resected mandible (Fig. 3a). In each of the analyses, the AO4 configuration also brought a reduction in the stresses on the mandibular cortical bone (Fig. 3b and c), consonant with some studies [5] but in contrast with others [19].

Regarding the stress concentration at the level of the implants (Fig. 5d), the simulations on patients with resected mandible presented maximum stresses that were lower than those on patients with whole mandibles, even though they exhibited distribution patterns placing considerable loads not only on the terminal implant of the loaded side but on other side as well (Fig. 5a and b). This was likely linked to the greater pliability of the bone-implant-prosthetic structure system at the level of the loaded side. Furthermore, the AO4 dynamic, by shortening the prosthetic cantilever, led to a decrease in stress at the level of the terminal implant on the loaded side (being nearer to the loaded point, it will always be subjected to the greatest stress [11]).

For the prosthetic superstructure (Figs. 3c, 4, 6c and d), the AO4 configurations led to smaller stress concentrations both in the simulations on the whole mandible and on the resected mandible, and with reductions that were nearly identical: this behavior too seemed to be the result primarily of the shortened distal cantilever. These data, in fact, would seem to indicate that whether the mandible is whole or not has no impact on the intensity of the stresses exerted on the prosthetic framework.

4.2. Conclusions

The following conclusions concerning fixed mandibular prosthetic rehabilitation using four implants for edentulous patients can be drawn:

- at the level of the implants, the greatest stress concentration always occurs in the area of the neck of the implants, specifically around the terminal implant on the loaded side. Where the rehabilitation is on a resected mandible, the other terminal implant is subjected to a greater load than in a whole mandible;
- at the level of the bone-implant interface in the simulations on the resected mandible, an increase in stresses is observed in the AO4 rehabilitation relative to its parallel-implant counterpart, whereas at the level of the external radial bone the exact opposite holds;
- AO4 rehabilitations always lead to a reduced stress concentration, both on resected and whole mandibles: the reduced length of the distal prosthetic cantilever represents the leading cause;
- the absence of constraints on the resected side of the mandible plays a part in determining the scale and the distribution pattern of the stresses at the level of the implants and of the cortical bone, but not at the level of the prosthetic framework;
- at the osseous level, the greatest concentration of stresses is at the level of the cortical bone.

4.3. Clinical relevance

The length of the distal prosthetic cantilever was shown to be critical to reduce mechanical stress at each level of the bone-implant-prosthesis system in both whole and resected mandibles. The prosthetic planning before surgery is paramount to reach such a result. In compromised mandibular anatomies, tilted distal implants used in the All-on-Four configuration seem to be an effective way to obtain it.

Declaration of Competing Interest

The authors have no potential conflict of interest to declare.

Acknowledgments

Profound gratitude goes to I. Fusco, DDS, and L. Marchi, DDS, for their great help in consulting the international literature, and also to S. Tellini, EngD and PhD, for his great contribution to the finite element analysis presented in this study.

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