

Relevant Anatomic and Biomechanical Studies for Implant Possibilities on the Atrophic Maxilla: Critical Appraisal and Literature Review

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Abstract

Purpose: The purpose of this review was to highlight anatomic and biomechanical aspects of atrophic maxillae for implant possibilities.

Materials and Methods: A MEDLINE electronic search of the years 1966 to 2009 was conducted with the keywords "atrophic," "resorbed," "edentulous," and "maxilla." **Results:** Twenty papers presented the following findings: (1) previous use of a removable prosthesis is a risk factor for resorption, with flabby tissues related to the severity of resorption; (2) implants in the reconstructed maxilla (≤ 5 mm) and supporting overdentures had a higher risk for bone loss based on the worse periimplant soft-tissue health observed; (3) bleeding on probing was found with pocket depths >5 mm in half of the zygomatic implants; (4) prevalence of bone septa is higher in atrophic maxillae, and changes on nasopalatine canal can reduce up to 44.4% of the full length of buccal bone plates; (5) female patients have less medullar bone quantity and connectivity than male patients; (6) transectioning of nutrient vessels is easier and accelerates resorption; (7) stress does not concentrate on maxillary sinus base cortical bone contiguous to trabecular bone; (8) splinted implants receive nine times less load than nonsplinted implants even under oblique loading; (9) implant stability quotient (ISQ) values for implants ranged between 60 and 65; (10) in vivo force transfer to implants is similar between fixed prostheses and overdentures; (11) inclined implants generate better biomechanical responses; (12) masticatory efficiency and bite forces improve in maxillectomized patients who receive obturators with milled bar attachments.

Conclusion: Sound implant-supported choices for an atrophic maxilla must be made with a thorough understanding of its anatomic and biomechanical factors.

The term atrophy is defined in the dictionary as "a wasting away; a diminution in the size of a cell, tissue, organ, or part."¹ According to Wolff's Law, "the bone remodels according to applied forces,"² and every time osseous function is modified, a definitive change on inner architecture and external configuration is seen.³ The lack of stimuli (disuse atrophy) seen on maxillary arches after tooth extraction is more intense at the first year and continuous throughout life,⁴ with many cases showing severe alveolar bone resorption in height and width. This phenomenon is variable, irreversible, and unpredictable, even for patients wearing immediate complete conventional prostheses.⁵ Nowadays, most of the esthetic and functional deficiencies generated by bone atrophy have been supplemented with several implant-supported/retained modal-

ities, accompanied or not by autogenous bone/biomaterial grafts. 6

In this sense, knowledge of anatomic and biomechanical problems at the atrophic maxillary arches is fundamental for adequate treatment planning and success of these reconstructions. The aim of this review is to provide clinicians with solid scientific aspects for a thorough decision-making process.

Materials and methods

To verify relevant anatomic and biomechanical studies, a PubMed/MEDLINE electronic search was conducted within the years of 1966 to 2009. The keywords "atrophic,"

"resorbed," "edentulous," and "maxilla" were combined and resulted in 472 studies (atrophic AND maxilla), 189 studies (atrophic AND edentulous AND maxilla), and 41 studies (atrophic AND resorbed AND maxilla). The MESH terms "biomechanics," "atrophy," and "maxilla" generated one study. Citations on anatomic and biomechanical issues were manually checked throughout the texts by two examiners (LMNR, WCB). Both in vitro and in vivo data were included; animal trials were not found. For the first reviewed aspect, not all articles described the degree of atrophy according to a standard classification published in the literature. Also, no randomized controlled clinical trials were identified for the second reviewed aspect. Finally, only 20 references regarding anatomy (nine studies: one laboratorial; two case series; two clinical; three anatomic; one cadaveric sections) and biomechanical characteristics (11 studies: 3 clinical prospective: 1 clinical, short-term: 2 clinical, cross-sectional; 2 clinical, case series, 1 anatomic, cadaver sections, 2 laboratorial, cross-sectional) were selected. Details of these data (classification of atrophic maxillary state, study design, groups, results, and conclusions) are presented in Tables 1 and 2.

Results

Anatomic considerations-extrinsic morphology

The atrophic maxilla is composed of a residual alveolar ridge and a mucous tissue of varied resilience. These two components make up its extrinsic morphology. Variations in height are seen along the ridges and provide clinicians a previous idea of implant length. Orthopantomographic analysis (magnification rate 1:1.25) of 173 edentulous maxillae (90 men and 83 women, mean age: 60 years) showed the following mean height values: median line = 16 mm, first premolar region = 16.5 mm, and first molar region = 15.5 mm, distance from the inferior border of maxillary sinus to alveolar crest = 6.3 mm;⁷ however, clinicians must remember that, even with such "enthusiastic" values, the degree of resorption at the alveolar ridge can also be severe. Another study showed previous use of a removable prosthesis was a risk factor for residual resorption (odds ratio = 2.4), as was the presence of a flabby tissue with the severity of resorption (odds ratio = 2.4); nevertheless, duration of edentulism in these patients was not a significant risk factor. When these 168 maxillae were compared to the panoramic radiographs of dentate patients, reductions in height at the anterior and posterior regions were of 18% and 11%, respectively.⁸

One of the first issues during treatment of maxillary atrophic arches is the achievement of adequate stability at the bone/implant interface. Fortunately, implant placement at posterior regions is not influenced by crest width, but related to the height of the ridges. After examining 47 histological sections, the authors verified that the height at the second premolar/first molar (M1) and at second molar (M2) regions ranged from 3.23 to 7.97 mm and 5.68 to 7.81 mm, respectively; however, it was observed that crest widths at 1 mm, 3 mm, 7 mm, and 10 mm above the top of the ridge (Cawood and Howell class VI) were for M1 and M2 regions, respectively, 3.31 and 4.42 mm, 6.86 and 6.45 mm, 14.07 and 10.2 mm, and zero.⁹ Compared to the nongrafted ridges, the transplanted bone and the overlying soft tissues of atrophic maxillae show different quality, quantity, and topographic characteristics. During analysis of 470 implants placed in 88 patients with severe atrophy (maxillary sinus thickness less than 5 mm), bleeding was observed in 46.2% in the overdenture group and 38.6% in cases with fixed prostheses. Also, bleeding and greater pocket depths were observed in groups with less than 5 mm of the initial maxillary sinus floor height. The thickness of keratinized mucosa was similar in both groups.¹⁰ Implants in the reconstructed maxilla and supporting overdentures had a higher risk for bone loss based on the worse periimplant soft-tissue health observed.

In the same way, soft-tissue health assumes a particularly important role on zygomatic fixtures and their associated prostheses with transmucosal abutments. When 20 implants were inserted in 14 patients, colonization by periodontal pathogens was observed at four implants. Further, nine implants demonstrated bleeding on probing, four of these with positive microbiological findings; sites without bleeding present negative results (p < 0.026). At sites with bleeding, pocket probing depths ≥ 5 mm were found, indicating soft tissue problems and a success rate of only 55%.¹¹

Over the years, some authors have categorized edentulous ridges (Atwood, ¹² Fallschüssel¹³); however, two classifications are the most used: Cawood and Howell's classification,¹⁴ which divides atrophic maxillae into four groups (class III = adequate height and width; class IV = knife-edge ridges, with adequate height, and inadequate width; class V = inadequate height and width; and class VI = depression found at ridges), and the Lekholm and Zarb classification,¹⁵ which implies a quantitative and qualitative analysis of residual alveolar bones (type 1 =large homogenous cortical bone; type 2 = thick cortical layer surrounding a dense medullar bone; type 3 =thin cortical layer surrounding a dense medullar bone; type 4 =thin cortical layer surrounding a sparse medullar bone). Both classifications, however, are bi-dimensional representations and do not show the three-dimensionality of atrophic ridges and associated defects, now evidenced by modern cone-beam computerized tomography (CT) techniques.¹⁶ Even so, most of the decision-making processes available in the literature were initially based on these classifications, and they still have their value for treatment planning.

Anatomic considerations-intrinsic morphology

After tooth extraction, increased osteoclastic activity and bone resorption lead to coronal maxillary sinus floor expansion.¹⁷ One study with reformatted CTs comparing the prevalence, height, location, and morphology of maxillary septa in 100 Korean patients (200 maxillary sinus in 41 women and 59 men), considered 85% of these sites atrophic (42.5% of patients). The prevalence of septa was significantly higher in atrophic than nonatrophic maxillar (31.76% and 22.61%, respectively); however, no differences among distribution of septa (anterior, middle, and posterior maxillary sinuses) were found, regardless of degree of atrophy. Also, differences of septa height between atrophic (2.84 mm) and nonatrophic (4.19 mm) maxillae were statistically significant (p < 0.05).¹⁸

Table 1	Relevant studies	on intrinsic and	l extrinsic anatomical	aspects for	implant	possibilities i	n the atrophic ma	axilla
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Authors (year)	Maxillary atrophic status	Design and studied parameters	Results	Conclusions
Güler et al (1995) ⁷	Nonspecified	Laboratorial, retrospective - 173 edentulous patients (90 men, 83 women) - vertical height measurements at eight maxillary sites (median line, premolar, and molars), based on panoramic radiographs	The most inferior border of maxillary sinuses are located anterior to the first molar in 48.9% (men) and 55.4% (women)	Results can aid clinicians on treatment planning for implant location
Ulm et al (1995) ⁹	Cawood and Howell	 Retrospective, undecalcified anatomic sections - 36 complete and 11 partially edentulous patients - alveolar ridge height measurements - alveolar ridge widths from 1 mm, 7 mm, and 10 mm below alveolar ridge crest 	For Cawood and Howell's class VI: height = 3.23 to 5.68 mm widths: (1 mm) = 3.31 to 4.42 mm (7 mm) = 14.07 to 10.22 mm (10 mm) = **	Bone widths in atrophic maxillae are efficient for implant placement
Xie et al (1997) ⁸	Moderate resorption: ≤15% in height Severe resorption: >15% in height	Clinical, retrospective - 168 edentulous maxillae - panoramic radiographic analysis - parameters: history of edentulousness, use of previous dentures, use of complete denture, denture-bearing soft tissue lesions, dental status of opposing jaw, and oral hygiene habits	 bone height decreases of 12% and 18% on posterior and anterior regions, respectively resorption not related to duration of edentulism, but to the quality of prosthesis previous use of removable prostheses contributes to resorption (odds ratio = 2.4) flabby tissue ridges related to severity of resorption (odds ratio = 2.4) 	Influence of local resorption factors was more pronounced in the maxillary arches
Ulm et al (1999) ²⁰	Lekholm and Zarb	Retrospective - 134 available histological sections (29 women, 23 men) at lateral incisor, first premolar and molar tooth regions - parameters: volume, thickness, number, and trabecular separation; trabecular bone pattern factor	All analyzed parameters present reduced amounts at the first molar region	Women showed less bone quantity and trabecular connectivity than men
Solar et al (1999) ²³	Cawood and Howell	Retrospective: 18 anatomic sections (Cawood and Howell's classes II and III) - topography of posterior superior alveolar artery (PSAA) and related anastomosis; location of infraorbital artery (IOA) - distance between caudal main branches with the alveolar bone, as well as emergence of these arteries	 Eight cases of extraosseous arterial anastomosis arterial lumen of PSAA and IOA are the same (1.6 mm). 	Transectioning of important arterial communications accelerates resorption
Kaptein et al (1999) ¹⁰	Original bone height below maxillary sinus floor: <5 mm (severe atrophy) >5 mm or more	 Clinical, prospective Group I: sinus floor <5 mm (77 patients, 433 implants) Group II: sinus floor ≥5 mm (11 patients, 37 implants) -maxillary sinus grafting with iliac crest bone and hidroxylapatite particles (3:1 ratio) restorations: overdentures or fixed prostheses parameters: probing depth, plaque, gingival, and bleeding indexes; keratinized mucosa 	 probing depths and bleeding on probing frequently observed on Group I significant increasing on peri-implant probing depth and gingival index of overdentures compared to fixed prostheses 	Implants on reconstructed maxillae with overdentures had more risk of bone loss based on the worst soft tissue periimplant observed condition

Continued

Authors (year)	Maxillary atrophic status	Design and studied parameters	Results	Conclusions
Al-Nawas et al (2004) ¹¹	Nonspecified (severe maxillary atrophy)	Case series, retrospective - 20 patients, 20 implants; 13 zygomatic fixtures (severe maxillary atrophy); and seven for tumor resection - microbiological analyses, DNA probes	 pathogens (4/20 implants) bleeding on probing (9/20 implants); four positive microbiological findings pockets ≥5 mm resulting in a 55% implant success rate 	Soft tissue problems must be considered when zygomatic implants are an alternative for maxillary arches
Kim et al (2006) ¹⁸	Nonspecified	Case series, prospective - 100 patients: 22% completely edentulous - 85 atrophic maxillary sinuses (42%) - septa height >2.5 mm - reformatted CTs: (field of view = 15 cm, 200 mA, 120 Kv, sections 1-mm thick, scanning time = 1 s)	 septa prevalence (27 of 85) lower septa height on atrophic maxillae no differences on septa location more frequency of primary septa on nonatrophic maxillae 	 wide anatomic variations for all investigated parameters regardless of atrophic state invaluable data to avoid complications on sinus augmentation procedures
Mardinger et al (2008) ¹⁹	Lekholm and Zarb: Class A: control group Classes B to E: study group	Case series, retrospective - 207 Korean patients - mapping of shape, length, diameter (the nasopalatine canal) - mapping of residual alveolar ridge, buccal to the canal opening - reconstructed CTs	 funnel-shaped canal (56.6%) on type E ridges canal lengths: from 10.7 mm (class A) to 9 mm (class E) buccal bone plate: 44.4% less than its original length. regions anterior to the canal: 60% less than their original thicknesses 	 the nasopalatine canal increases in all directions and after aging the palatal opening is 32% enlarged and can occupy up to 58% of the alveolar width at potential sites for two central incisors implant placement

** According to Ulm et al, "In class 6 (extremely resorbed ridges), the measurements of width of the alveolar ridge at 10 mm below the ridge crest could not be made, as the alveolar ridges grouped in this class were markedly lower than 10 mm."

Progressive bone loss can also result in approximation of alveolar ridges and important anatomic structures (nasopalatine canal), preventing implant placement.¹⁹ One study with 207 individuals verified these changes based on Lekholm and Zarb's classification (classes A to E). The canal length decreased from 10.7 mm (class A) to 9 mm (class E). The canal diameter increased as the resorption proceeded. The mean increase in diameter (classes B to E) was 1.8 mm (32%) at the palatal area and 0.7 mm at the nasal canal region. For the severely resorbed maxillae (classes C, D, and E) and when the canal was positioned over the ridge, 35.6% of the proposed site for the central incisor was occupied. The buccal bone plate lost almost 44.4% of its full length, reducing from 17.22 mm (class A) to 9.57 mm (class E) (p < 0.01). The buccal bony plate anterior to the canal lost 60% of its mean width and reduced from 6.4 mm (class A) to 2.6 mm (class E) (p < 0.01).

By means of histomorphometric studies, the trabecular pattern of atrophic edentulous maxillae was analyzed in 62 cadavers (29 women and 23 men) resulting in 156 sections with 5 mm of thickness, at the lateral incisor (I2), premolar (P1), and molar (M1) sites. When these sections were grouped according to Lekholm and Zarb's classification, types 1 and 2 were not found: for types 3 and 4, the following incidence values were seen (for men and women): (I2 = 82.61% and 82.76%; 17.39%)and 17.24%), (P1 = 77.78% and 72.41%; 22.22% and 27.59%), and (M1 = 38.46% and 31.82%; 61.54% and 68.18%). Still, using 134 undecalcified sections of the same regions, the authors quantified the bone trabecular volume (I2 = 20.2 to 27.9%; P1 = 20.5 to 26.7%; M1 = 17.1 to 23.4%), mean trabecular thickness (I2 = 112 to 133 μ m; P1 = 121 to 138 μ m; M1 = 95 to 118 μ m), mean trabecular number (I2 = 1.81 to 2.07 mm⁻¹; P1 = 1.68 to 1.91 mm⁻¹; 1.76 to 1.95 mm⁻¹), mean trabecular separation (I2 = 363 to 480 μ m; P1 = 412 to 507 μ m; M1 = 424 to 535 μ m), as well as the trabecular bone pattern factor (TBPF) (I2 = -1.106 to 0.171 mm⁻¹; P1 = -0.562 to 0.450 mm^{-1} ; M1 = $-0.078 \text{ to } 0.123 \text{ mm}^{-1}$). In most cases, the

Table 2 Relevant studies on biomechanical aspects for implant possibilities on the atrophic maxilla

Authors (year)	Maxillary atrophic status	Design and studied parameters	Results	Conclusions
Mericske- Stern et al (2000) ³⁵	Nonspecified (the patient had a maxillary implant- supported overdenture)	Clinical, cross-sectional - one patient (49 years old) - five implants (3 years of use) - piezoelectric transducers - maximum bite force: centric occlusion and bite plane studies on overdenture (two bar designs) and fixed prostheses - selected chewing foods: bread, apples	 similar forces on both implant-supported prostheses greater forces on posterior implants and along the long axis vertical similar forces on food chewing 	 similar force patterns for overdenture and fixed prostheses. overdenture's bar design did not influence force patterns
Duyck et al (2000) ³⁶	Nonspecified (patients wearing their prostheses with success for 0 to 12 years)	Clinical, cross-sectional - four patients (maxillary arch) - extensometers (20 registrations) - 50 N load - forces measured first on three to four implants and five to six implants later	 greater forces with reduced implant numbers compressive forces on implants near application point 	Higher bending moments with only three implants activated; more clinical research is necessary.
Meyer et al (2001) ²⁶	- atrophic maxilla (8-mm height) - mean maxilla (12-mm height)	Laboratorial, cross-sectional - FEM mesh with 10,000 elements - bicortical fixation, two cortical bone modalities (2 mm and 0.5 mm) - 150 N axial loading	 stresses three times lower in the buccolingual direction microstrains around implant neck: thick cortical (4000), lack of cortical (5000), reduced bone height (6000) 	Supraphysiological bone deformations can be expected for implants in the atrophic maxillae
Fortin et al (2002) ³⁷	Bone height: 10 mm at posterior region	Clinical, prospective - immediate loading - 45 patients; 245 implants - 5-year follow-up - Marius bridge concept	 implant success rate: 97% prosthesis success rate: 100% few prosthetic failures without compromising overall patient well-being and prosthesis wear 	Treatment type is effective and predictable; removable prosthesis can be considered a fixed type still providing lip support and adequate
Olsson et al (2003) ³³	Nonspecified. Lekholm and Zarb's classification for bone density	Clinical, case series - ten patients; 61 oxidized implants - RFA (resonance frequency analysis)	- bone loss (1.3 mm/year) - ISQ values: 60.1 and 62.8 after 4 months.	Predictable immediate loading over six to eight implants in the atrophic maxilla; however, more longitudinal studies are necessary
Fukuda et al (2004) ³⁹	Nonspecified	Clinical, case series - seven maxillectomized patients (bone and sometimes muscle grafts); (some at HBO therapy) - parameters: masticatory function (questionnaire), biting capacity (pressure detector), speech (Hirose's score: 0 to 8 points); marginal bone loss (radiographs)	 improvements on masticatory function (77.1 points), biting capacity (317.9 N) and speech (mean of five points) bone loss: 0.42 mm (first year), 0.61 mm (follow-up) 	Obturator prostheses on milled bars are useful on oral rehabilitation of tumor resected, edentulous maxillary patients
Hallman et al (2005) ³²	Cawood and Howell classes IV and V (posterior region); classes III and IV (anterior region)	Clinical, prospective follow-up - 20 patients, 108 implants - bovine and autogenous bone graft (80:20 ratio); implants placed 6 months after - RFA, CTs, and marginal bone loss	 implant survival rate: 86%- ISQ 66 for residual and grafted bones (after 3 years) bone loss: 1.3 mm after 3 years 71% of healthy maxillary sinuses according to TCs 	Maxillary sinus grafting with a mixture of autogenous and bovine bone is a reliable procedure.

Continued

Authors (year)	Maxillary atrophic status	Design and studied parameters	Results	Conclusions
Nomoto et al (2006) ²⁸	Nonspecified. Three- dimensional (3D) bone morphometric analysis	Laboratorial, cadaver model - 10 Japanese patients - micro-CT-based FEA - loads on first molar, corresponding alveolar region, and with implant placed	 stress around cortical bone only in the edentulous maxilla stresses around implant similar to that found around first molar 	A model simulating trabecular bone allows more precise evaluation on stress distribution
Sjöström et al (2007) ³⁰	Cawood and Howell	Clinical, prospective - 29 patients iliac crest bone grafts - 192 implants inserted 6 to 8 months later -RFA (four times)	 premature failure (20 implants) ISQs: 60 (abutment connection), 62.5 (after 6 months), and 61.8 (3 years of use with definitive prosthesis) marginal bone loss (0.3 mm) 	ISQ values serve as risk indicators for implant loading on atrophic maxillae
Ujigawa et al (2007) ²⁷	Nonspecified (severely resorbed maxilla)	Laboratorial- CTs from a 68-year - old patient- mesh with 112,000 nodes for FEA - zygomatic implant splinted to the remaining infra-structure or not - applied loads: axial (150 N), lateral (50 N)	 nonsplinted implant: stress on the zygoma bone, median implant region, and implant abutment junction - no stress on the alveolar bone of the splinted implant 	The stress is supported by zygomatic bone, distributed along the infrazygomatic crest, and divided between the frontal and temporal processes of zygomatic bone
Veltri et al (2008) ³¹	Cawood and Howell	 Clinical, short-term 12 patients: eight women, four men 73 implants with surface treatment (Ø = 3.5 mm) prostheses inserted 6 months later RFA measurements radiographic marginal bone loss 	 implant success rate: 100% (1 year of function) ISQs: 63 (implant placement), 60 (abutment connection), 61 (1 year later); bone loss: 0.3 mm (after 1 year of loading) 	Narrow implants can be used to restore class IV atrophic maxillae as alternative to complex grafting techniques

buccal and alveolar compartments were reduced, compared to the palatal ones. Women showed less medullar bone quantity and connectivity than men.²⁰

One important aspect also observed in atrophic maxillae is that pneumatization at the sinus floor and continuous medullar bone loss result in a thin ridge at posterior regions; thus, nutrient vessels (arteries) to the alveolar process present a small-sized lumen, from a centromedullar to an exclusive mucoperiosteal origin. Thus, minimally invasive techniques avoiding too much bone exposition would prevent considerable resorption at host bone areas on healing.²¹ Also, clinicians must observe two important communications: one between the infraorbital artery and the capillaries overlying the alveolar process, and the other between the infraorbital artery and the posterior superior alveolar artery inside the bony wall of the maxillary sinus.^{22,23} For example, severing of these vessels that keep the regional blood flow during sinus lift or grafting procedures can lead to unexpected bone resorption and poor healing of the grafts.²⁴

Biomechanics in the atrophic maxilla

Available studies on biomechanics were represented by finite element analysis (FEA), resonance frequency analysis (RFA), or strain-gauge/force transducer measurements. Even thus, the information is still scarce, with most studies represented by prospective or retrospective case series.

First, one must understand masticatory load distribution in totally dentate individuals: mandibular molars transmit load to the upper molars, where the lingual and the two buccal roots decompose the overall force vector to the cranial base. When FEA was performed based on CT models, the maxillary sinus showed the highest stress and deformation rates; also, similar findings were seen at the hard palate region and at the posterior bony portion of the nasal septa (vomer and perpendicular plate of ethmoid bone). In this way, bones lateral to the maxillary sinus underwent stress coming from buccal roots, as forces from the lingual roots are spread on the palatal septa complex (bones medial to the maxillary sinus).²⁵

Under mechanical loading, FEA of implants inserted on normal and atrophic maxillae show supraphysiological bone strain at the implant surface on the latter. Stresses are more homogenous when more spongy bone is found. An atrophic ridge combined with inadequate bone quality generates up to 6000 microstrains at surface level. Here, less importance is given to the bone crest on the quality of dissipation stress and strains under mechanical cycling.²⁶

Axial loading (150 N) on zygomatic implants splinted to conventional fixtures or not and lateral loading (50 N) at the

palatal surface of suprastructures were conducted. The stresses concentrated around the alveolar bone in the splinted mode. On the other hand, the stresses are generated on the zygoma bone, middle part of the fixture, and at the implant/abutment interface. First, the zygoma withstands the stresses from occlusal forces, which transfer them to the infrazygomatic crest, being divided at the frontal and temporal process of zygomatic bone in several directions.²⁷

Micro-CT techniques were added to the FEA studies on atrophic alveolar maxillary ridges of ten adult cadavers (five dentate). Occlusal loads applied to the first molar region in the dentate model and at the corresponding alveolar ridge showed that in the former, the stress concentrated at the cortical bone and around the maxillary sinus floor adjacent to the trabecular bone of dental roots. In the latter, stress was found at the cortical bone of the alveolar ridge, but also on the inner trabecular bone; however, no stresses were observed at the cortical bone of the maxillary sinus floor adjacent to the trabecular bone. This cortical bone of the edentulous model only showed stresses when a cylindrical body 4 mm in diameter and 10 mm in length was modeled at this region.²⁸

The bone/implant interface in the edentulous region can be protected by splinting of implants with a fixed prosthesis after surgery. This treatment modality is used most often and only recently confirmed by FEA. As expected, stresses around splinted implants are nine times lower than in nonsplinted models, even when a simulated acrylic fixed prosthesis received 10° oblique loading of 300 N.²⁹

On the other hand, Frequency Resonance Analysis is helpful to determine the moment of loading and to verify implant stability, mainly on treatment of atrophied maxilla with simultaneous bone grafts. These demonstrated good stability quotients after 3 years of implant loading. Twenty-five patients received 222 implants distributed according to Cawood and Howell's classification in the following way: class III = 17, class IV =67, class V = 111, class VI = 25, no classification = 2. Implant Stability Quotient values showed statistically significant differences between abutment connection (60.2) and 6 months after loading (62.5), but these were not confirmed between 6 months and 3 years after loading (61.8). A multivariate logistic regression analysis indicated that factors such as gender (women) and implants at class VI before reconstruction significantly increased the risk of failure.³⁰ Preliminary results show that reduced diameter implants (3.5 mm) can be used with success on atrophic maxillae (Cawood and Howell's class IV) to avoid grafting procedures.³¹ When implant-supported fixed prostheses were delivered after 6 months of healing, the implant survival rate was 100%, and bone loss registered around 0.3 mm; mean ISQ values were 63 (baseline), 60 (abutment connection), and 61 (1 year after loading). Also, the use of deproteinized bovine bone (autogenous bone + Bio-Oss, 20:80 ratio) after sinus lifting and implant loading (12 months) in atrophic maxillae generated ISQ values (65.6) very similar to nongrafted sites (67.4).³² Finally, the use of surface-oxidized implants and definitive implant-supported prostheses generated values similar to those described above.33

Even in the resorbed maxilla, the bearing support area is two times greater than in the mandibular arch.³⁴ The use of piezo-electric force transducers revealed no differences on force trans-

ferring, regardless of prosthesis type (fixed or overdenture); however, magnitude of forces was higher in posterior implants, whereas on anterior implants, transversal forces reached up to 100% or more of axial forces during mastication. Although only one atrophic maxilla was used in this study, these values were confirmed 2 years later.³⁵ A reduced number of conventionally placed implants in the atrophic maxilla is not recommended, and force distribution only resolves when five to six implants are used;³⁶ however, the use of inclined implants along with a removable overdenture (Marius bridge) showed a 97% survival rate (five failures of 245) after 5 years, with ten related mechanical complications (one fracture of mesostructure, nine problems with attachments).³⁷

One of the greatest difficulties is improving the biomechanical response in patients with tumor resections. One study showed that peri-implant resorption rate depends on implant location.³⁸ Conversely, when obturators are constructed with bar milled attachments, either masticatory efficiency (16 to 77 points) or bite force (317 N) is improved.³⁹ Another important situation is the edentulous state with cleft lip and palate defects, where experience and creativity are needed to achieve the desired prosthetic rehabilitation.⁴⁰

Discussion

In this review, important anatomic (morphological intrinsic and extrinsic) and biomechanical aspects on the atrophic maxilla were highlighted. The centripetal resorption pattern described in the maxillary arch makes bone the most precious source for facial and dental esthetics. In this way, every attempt to alleviate this condition is mandatory.

The use of a complete conventional maxillary prosthesis and a Kennedy class I removable denture in the mandibular arch is a common clinical finding, as is the presence of flabby tissues in the maxillary anterior and posterior regions, attributed to the mechanics of "combination syndrome."⁴¹ Because both are considered risk factors influencing the severity of bone resorption, and not all patients can afford implant therapy, the clinician's role is to guarantee periodic denture base relining and to identify lack of adequate performance on prosthetic devices.

Factors related to the height of bone septa and changes on the nasopalatine canal reveal that these features can only be viewed in detail with modern CT techniques; thus, comprehensive interaction between clinicians and nuclear radiologists for a thorough bone evaluation is important, because presence and location of septa compromise maxillary sinus lifting procedures. The inclusion of considerable enlargement at the nasopalatine canal as a consequence of disuse atrophy is relevant. Also, these two anatomic changes mean a need for screening different populations to identify other possible characteristics related to the atrophic maxillae.

Although zygomatic implants have been considered an interesting resolution for atrophic maxillae, and the use of long transmucosal abutments is inevitable, the likelihood of bleeding on probing is increased. Further improvements on prosthesis design are necessary to reduce biological complications.

In the atrophic maxillae, stress does not concentrate on cortical bone at the maxillary sinus base continuous to trabecular bone. This constitutes an attempt for generating more accurate models with FEA studies based on bone micro-CT analysis. One possible indirect assumption here is that sinus floor pneumatization really has no opposing occlusal forces. Also, densitometric bone parameters used in this article were very similar to findings reported almost 10 years ago in another study²⁰ cited in this review.

ISQ values for implants placed in severely atrophic maxillae ranged from 60 to 65, which confirms the effect of splinting tested with finite element models to avoid bone damage evolution: however, these values did not diminish the risk of failures in Cawood and Howell's class VI. Even thus, successful application of narrow-diameter implants is possible in class IV cases. In addition, the use of inclined implants has been popularized in the atrophic maxilla, with good clinical survival rates already published.^{42,43} Finally, the observation that prosthesis type (fixed or overdenture) does not influence in vivo force transfer can help clinicians decide for a more esthetic alternative when considerable lip support must be addressed. Surprisingly, biomechanics on the result of acquired maxillary atrophic deficiencies (tumor resection, cleft patients) remains an exciting but not totally explored area, given its implications on social behavior and quality of life; however, technological improvements on implant surfaces and macro/microdesigns will have a considerable impact here in the near future.

Conclusion

Clinicians must understand the possible anatomic and biomechanical implications of atrophic maxillary arches to prevent or avoid failures, as well as to meet patients' expectations based on sound choices of available biomaterials and technologies for implant-supported prostheses.

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