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Recent advances of ultrasound imaging in dentistry − a review of the literature

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Ultrasonography as an imaging modality in dentistry has been extensively explored in recent years due to several advantages that diagnostic ultrasound provides. It is a non-invasive, inexpensive, painless method and unlike X-ray, it does not cause harmful ionizing radiation. Ultrasound has a promising future as a diagnostic imaging tool in all specialties in dentistry, for both hard and soft tissue detection. The aim of this review is to provide the scientific community and clinicians with an overview of the most recent advances of ultrasound imaging in dentistry. The use of ultrasound is described and discussed in the fields of dental scanning, caries detection, dental fractures, soft tissue and periapical lesions, maxillofacial fractures, periodontal bony defects, gingival and muscle thickness, temporomandibular disorders, and implant dentistry. (Oral Surg Oral Med Oral Pathol Oral Radiol 2013;115:819-832)

Ultrasound refers to the acoustic waves with frequencies higher than 20 KHz, which correspond to the upper limit of sound audible to humans.[1] For most medical applications, wave generation is based on electromechanical transducers using piezoelectric materials.[2] Benefits of ultrasound modalities include the relative low costs, as well as real-time abilities of most diagnostic devices, and the assessment of mechanical material characteristics such as bulk or shear moduli. Ultrasound waves transmit energy, as X-ray does, but while X-rays pass readily through a vacuum, sound requires a medium for its transmission.[3]

Generally, the speed of sound is faster in solids, intermediate in liquids and slow in gases. In an ideal liquid, the bulk modulus of shear is zero. Most real liquids behave like an ideal liquid, which means that the energy transportation is dominated by longitudinal waves too. The propagation speed of the ultrasound wave in a liquid relies on the particle density and the bulk modulus of compression. As a first approximation, soft tissues can be considered as a viscous fluid. Due to the fact that densities and compression modulus of most soft tissues are similar to that of water at 37 °C, a mean propagation speed of 1540 m/s is assumed for the most common case of brightness modulated (B-mode) pulse-echo imaging.[2] Nevertheless, variations in speed of sound either due to the heterogeneous soft tissue distribution or even local temperature differences can cause distance measurement errors and refraction based image distortion. More complex cases arise if hard tissues, like tooth and bone, are in the focus of interest. Hard tissues show a much higher speed of sound variation than soft tissues. Furthermore, shear modulus dependent waves can occur in addition to the longitudinal wave mode. Interface effects should be considered, and energy loss inside of high-attenuating tissues, like bone, may be a limiting factor for the B-mode imaging.

At high levels of exposure, ultrasound waves can damage tissues, in addition to having teratogenic effects, due to heat, and acoustic cavitation. However, within the diagnostic range at low intensities and pressure levels, the probability for heating beyond the normal physiological range, or cavitation in the absence of gas bubbles is very low.[4]

Ultrasound has been used in medical fields for decades. 3-D fetus ultrasonography and contrast enhanced imaging using microbubbles are only some of the advances in this field. In order to obtain an image of a structure, the ultrasound system transmits high frequency pulses, e.g., in the range of 2-20 MHz, inside the tissue. At the boundary between two distinct tissues

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Statement of Clinical Relevance

This review article provides for the scientific community and for clinicians as well, an overview about the most recent advances of ultrasound imaging in dentistry.

of different acoustic impedances, a part of the emitted pulse is reflected, and another part is transmitted. Depending on the impedance mismatch at the boundaries, the portion of the reflected pulse varies. For example, at the boundary between soft tissue and bone, up to 40% of the energy of the incident pulse is scattered back. Only those parts of the reflected wave, which are in the same direction as the incident wave, can be captured by the same probe, which converts the pressure waves into radio frequency (RF) voltage traces. This method is well known as pulse echo ultrasound.

The most commonly used display modes in dentistry are A (amplitude) and B (brightness) mode.[3] B-mode ultrasound images can be calculated e.g., by mechanically moving a single element ultrasound probe on a trajectory (e.g., a line), receiving RF-echo traces from each probe position and then reconstructing an ultrasound image after several signal processing steps (Figure 1). Demodulation followed by envelope detection, logarithmic compression, two-dimentional (2-D)-filtering, gray scaling and scan conversion to fit the desired display system are the most common practice. If only the amplitude demodulated voltage trace is displayed, this corresponds to an A-mode ultrasound image.[3] A-mode ultrasound is the most basic display mode right after plotting the RF-signal. Single element ultrasound systems suffer from fixed focus and a limited depth of field. In modern diagnostic ultrasound machines, mechanically moved single element transducers have been replaced by ultrasound array technology. Comparable to radar phased array systems, this technology allows for electronically focusing and steering the ultrasound transmit beam as well as for dynamic receive focusing and filtering based on any kind of (digital) beamformer.[3] However, ultrasound array systems are much more complex than single element systems which makes them much more difficult to build particularly in case of high frequency applications (>50 MHz).[3]

B-mode is the most commonly used display mode in diagnostic ultrasound. In echocardiography, time-motion (TM)-mode is used in some cases. In TM-mode, a single A-mode trace is gray scaled and displayed against time e.g., making the movement of the heart valve visible. Three-dimentional (3-D) ultrasound has been introduced for 3-D scanning and reconstructing a volume of ultrasound scatters. 3-D ultrasound can be realized by either manually (e.g., optically tracked) or mechanically moving a one-dimentional (1-D) ultrasound array or by 2-D array technology. If a 3-D volume is recorded over time and if the frame rate is high enough to cover a single cardiac cycle, this technique is called (four-dimentional) 4-D ultrasound.

The first data of diagnostic ultrasound in dentistry reported in the literature seems to be in 1963 by Baum et al.,[5] who used a 15 MHz transducer with the aim of visualizing the interior structures of teeth; however, the quality and clarity of the resulted RF signal was not favorable.[6] Since then, many new and different ultrasound applications in dentistry have been reported.[6-15]

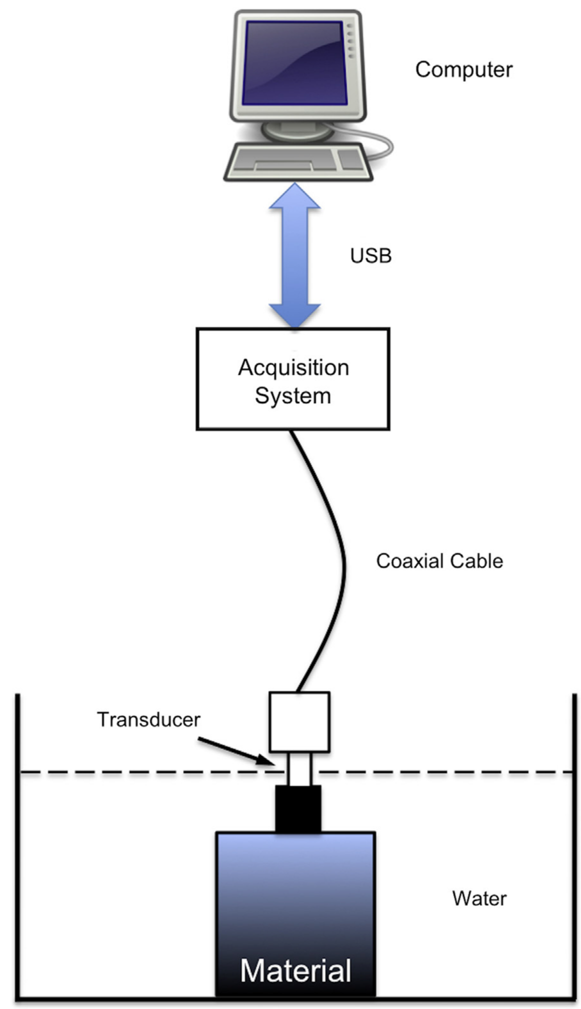

Fig. 1. Diagram showing pulse echo method of ultrasound imaging. The material to be scanned is placed in a tank filled with water, and then the ultrasound transducer is coupled to the system. A coaxial cable transmits the pulses to an image acquisition system, and then this image is processed in the computer by specific software.

Investigations have been performed in order to explore the ability of ultrasound to detect carious lesions, dental fractures or cracks, soft tissue lesions, maxillofacial fractures, periodontal bony defects, measurement of muscle and gingival thickness, diagnosis of temporomandibular disorders, implant dentistry and dental scanning. Conventional radiography (e.g., periapical and panoramic) and computed tomography (CT) are conventional diagnostic tools, but they generate ionizing radiation, which may be harmful to the patient and for this reason cannot be repeated indiscriminately.

Table I. Recent publications of ultrasound imaging in dentistry

Ultrasound imaging in dentistry	
Indications	*Literature*
Dental scanning	Culjat[16], Bozkurt[20], Sun[7], Hughes[21], Harput[13], Slak[19], Salmon[2]
Caries detection	Ghorayeb[23], Matalon[24,25], Pretty[22], Tagtekin[14]
Dental fractures and cracks	Culjat[26], Singh[27], dos Santos[28]
Soft tissue lesions	Friedrich[30], Wakasugi-Sato[29], Pallagatti[31], Chandak[32], Yamamoto[33]
Periapical lesions	Cotti[34,35], Gundappa[37], Rajendran[36], Aggarwal[38], Tikku[10], Goel[39], Maity[40]
Maxillofacial fractures	Blessmann[41], Park[43], Nezafati[44], Adeyemo[42]
Periodontal bony defects	Tsiolis[46], Ghorayeb[6], Mahmoud[11], Xiang[17], Chifor[8]
Gingival thickness	Cha[52], Savitha[50], Müller[49,58]
Muscle thickness	Ariji[56,57], Kiliaridis[59], Serra[53], Müller[58], Trawitzki[60], Naser-ud-Din[61]
Temporomandibular disorders	Manfredini[62,66], Parra[67], Çakir-Özkan[64], Kaya[63], Bas[9,68], Jank[65]
Implant dentistry	Culjat[69], Machtei[70]

Moreover, while CT is expensive, radiographs do not provide additional morphological information, such as that found in ultrasonography, and they are usually not well accepted by patients.[2,3,16,17]

The aim of this review article is to give an updated overview about the applications of diagnostic ultrasound imaging in dentistry, focusing on new advancements based on the most recent publications in the literature.

REVIEW OF THE LITERATURE

Method

The searching method for identifying scientific reports included searching the electronic database MEDLINE (PubMed), from October 2011 until May 2012, conducted by three independent reviewers, using the terms: *ultrasound, ultrasonography, image*, *dentistry* alone or in combination with one or more of the following terms: hard tissue, soft tissue, dental implant, tooth, enamel, dentin, caries, fracture, cracks, periapical, lesion, gingiva, temporomandibular disorder, muscle thickness, dental scanning, acoustic properties. Related citations were also checked. All titles revealed by this search strategy were screened, and after this an abstract search was conducted to identify articles that could be of possible relevance. From the abstracts included, full-text articles were chosen. The reviewers resolved any disagreements concerning the assortment of articles by discussion. The study selection criteria included articles related to ultrasound image and dentistry, or ultrasound image in the head and neck region. Articles that described basic principles of ultrasound and the acoustic properties of tissues were also included in the search criteria. The exclusion criteria were the absence of the abstract or full paper, studies older than 10 years, and in languages other than English.

Results

From 4125 articles revealed by the electronic search, the reviewers first selected 252. After agreement, 58 articles were finally chosen, and these are specified in Table I and commented in this review.

Discussion

Dental scanning. Most solids, including enamel and dentin, can be penetrated by ultrasound, and it is possible to detect caries and cracks that can usually hardly be observed in conventional film radiography.[18] Figure 2 gives an example of the image formed by ultrasound.

Culjat et al.[16] reported the results of a 2-D image scan of a human maxillary third molar and its underlying dentinoenamel junction using ultrasound frequencies in the 10-MHz range. Due to the irregular tooth anatomy, some errors were evident in the ultrasonic images because, as the ultrasonic beam hits sharp or undulated surfaces, it is usually distorted upon reflection and transmission, leading to errors in the A-scan pulse echo trace and the resulting cross-sectional image. In order to try to understand these problems and facilitate diagnosis, a 3-D finite element simulation study for ultrasonic propagation in the tooth was conducted by Sun et al.,[7] in which caries lesions were also simulated on the models. Finite element modeling simulation has the advantage of analyzing a single parameter without modification of shape, size, loading or testing environment. It was observed that the influence of a particular pathology could be studied without the impact of tooth structural variation, such as geometry and boundary conditions. The authors concluded that the simulated response of the ultrasonic loading pulse showed excellent replication of the results obtained from in vitro tests.

As the acoustic properties of enamel, dentin and soft tissue have already been established (Table II), studies can be performed in phantom models in order to facilitate ultrasound imaging analysis.[18] However, to the best of our knowledge, there is still no report in the literature concerning the acoustic properties of periodontal tissue, which is also important information that can be obtained by means of ultrasound scanning.

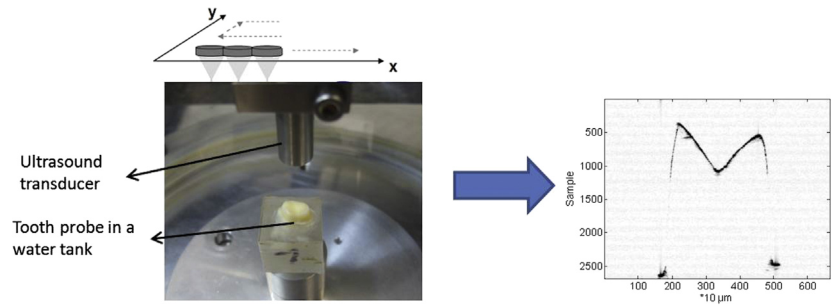

Fig. 2. In the picture on the left, the scan process of a tooth can be seen, using an ultrasound transducer. The picture on the right shows a representation of the processed image, representing a tooth slice in gray scale values.

Slak et al.[19] reported the use of a high frequency ultrasonic transducer-based hand-held probe to assess enamel thickness. The enamel thickness values obtained with the use of the hand-held probe vs. the acoustic microscope were in close proximity (~10% difference) and were also satisfactorily close to the enamel thickness results obtained from the direct cross-sectional measurements (~12% difference). The authors suggested a measuring procedure that would allow the avoidance of errors related to localization of the ultrasonic beam on the tooth surface. The high feasibility of the ultrasonic pulse-echo measurements in a hand-held mode was demonstrated.

Harput et al.[13] also measured the thickness of the enamel layer by means of ultrasound with a frequency of 15 MHz. A fractional Fourier transform (FrFT) was utilized to analyze overlapping echoes, which are caused by the successive reflections inside the enamel and dentin layers. A tooth phantom was then constructed to test the effectiveness of the proposed technique and the experimental measurements were performed in the tooth phantom and an extracted human molar. The FrFT was used for dental imaging in order to separate chirp signals overlapping in both time and frequency domains. The overlapped chirps were compressed using the FrFT and matched filter techniques. Micro-computed tomography was used for validation of the proposed technique. The authors concluded that the proposed contact imaging method combined with coded excitation and the FrFT technique can be used as a diagnostic tool in dentistry to measure enamel thickness, locate cracks inside the tooth, and analyze potential restoration faults. Similar results were obtained by Bozkurt et al.,[20] who evaluated the effectiveness of ultrasound to measure the thickness of enamel with an 11 MHz transducer.

Hughes et al.[21] investigated human dental samples with a B-scan high frequency transducer to evaluate enamel thickness. The transducer used had a center frequency of 35 MHz, and a −6 dB bandwidth of 24 MHz. The authors estimated that in order to observe a variation in thickness of 10% in enamel, during early decay as a result of acid erosion, for example, a minimum frequency of 22 MHz would be necessary. So by using a 35 MHz transducer, they expected to have a significant improvement in the axial resolution of enamel, around 180 μm, as well as a higher spatial and temporal resolution, and therefore, a more accurate profile of the enamel layer to be recorded. After submerging the samples in water, the enamel-dentin junction depth was measured and compared with measurements from the sequential grinding and imaging method. The B-scan showed that the measurements had a correlation of 0.89 ($P \leq .01$). The authors concluded that this high frequency ultrasound was able to measure enamel thickness to an accuracy of within 10% of the total enamel thickness, corresponding to within 50 μm of sequential grinding and imaging method measurements taken on the same sample.

Table II. Acoustic properties of tissues[18,26]

Material	*Velocity (m/s)*	*Acoustic impedance (MRayl)*	*Density (kg/m^3)*	*Elastic coefficient (10^9 N/m^2)*
Enamel	5700	16.5	2100	109.8
Dentin	3800	8.0	2900	33.5
Soft tissue	1540	1.63	1043	–

A recent study conducted by Salmon et al.[2] provided interesting information about a brightness-mode (B-mode) 25 MHz high-frequency ultrasound prototype developed for intraoral imaging. The authors presented images in which the tooth and periodontal structures could be visualized, in addition to being able to measure them, as well as dental implants and a mucocele. The study was conducted in three volunteers, without periodontal disease, whose teeth were explored on the buccal and lingual sides (162 samples). Despite the small sample size, patients felt that oral ultrasonography was a stress-free, painless, and rapid examination (less than 1 min for each area), possibly due to the small size of the probe and its design. The authors affirmed that the device still needs some improvements, but it is very promising for large-scale used in clinical studies, in order to validate its diagnostic value and determine whether it should remain a research tool.

Caries detection. Considering the importance of detecting caries lesions at an early stage and correctly quantify the degree of mineral loss to ensure that the correct intervention is implemented, a range of new detection systems have been developed, and among them, ultrasound imaging technology.[6,22]

Ghorayeb et al.[23] analyzed the integrity of human teeth by means of A- and B-scan ultrasound. Four teeth were examined: (1) intact; (2) with amalgam restoration and a natural surface fissure; (3) with a 1-mm diameter hole drilled to simulate a caries cavity; (4) and a calcified tooth. A 10 MHz transducer with an aperture diameter of 0.63 cm and a focal length of 1.27 cm was used. The A- and B-scans were collected when all teeth were mounted in the upright position. Enamel and dentin thicknesses were estimated from the time of flight information in the A-scan obtained for the intact tooth. By means of finite element and transmission line analyses, the results showed that ultrasound imaging is a promising tool for assessing the integrity of teeth. Nevertheless, due to the natural complexity of the tooth structure, the authors affirmed that it was not possible to draw any firm conclusions about the predictability of the results.

Tagtekin et al.[14] compared the DIAGNOdent with ultrasound for caries detection. The DIAGNOdent (KaVo, Biberach, Germany) is able to perform diagnosis, based on the fluorescence emitted from carious surfaces when they are irradiated with a laser beam at a wavelength of 655 nm. Carious lesions ($n = 42$) were captured by a digital camera and measured by test methods and confocal laser scanning microscope. Using DIAGNOdent, intra-observer agreements were 78.5%, 66.7% for A tip and 59.5%, 47.6% for B found by 2 examiners, respectively. Accuracy of both tips was 50% for the first examiner, 45.3% for A and 47.6% for the B tip for the second examiner. All ultrasound measurements were accurate, reliable, and positively and significantly correlated between examiners. The authors showed that both methods demonstrated high repeatability and accuracy.

Pretty[22] conducted a literature review about different image diagnostic techniques for caries detection. The author concluded that there is still limited evidence supporting each technique, often due to a failure of standardization and limited clinical studies. As regards ultrasound for caries detection, encouraging findings have been reported, but there are still limited studies.

Matalon et al.[24] compared traditional bite-wing radiography with ultrasound for diagnosis of approximal caries. For this study, 36 extracted premolars and molars were selected after undergoing previous examination and caries detection. Each tooth, placed upright in the same set-up as in the radiographs, was then examined independently by seven clinicians using ultrasound. Examinations were repeated after 1 week to record the intraexaminer reproducibility. The real interproximal caries diagnosis was validated with the use of stereomicroscopy. The efficacy of the ultrasound diagnostic device for cavitated carious lesion detection was assessed by determining its specificity and sensitivity, 1.0 for each, in comparison with those of bite-wing radiography, 0.92 and 0.90, respectively ($P \leq .001$). The mean receiver operating characteristic value for the area under the curve was 0.934 with bite-wing radiography and 1 with the ultrasound diagnostic device. These results showed that under in vitro conditions, ultrasound is reliable for detecting approximal carious lesions, and has a similar level of accuracy to that of bite-wing radiographs, with the advantage of not promoting ionizing radiations as is the case with X-rays. Furthermore, a similar study was conducted by Matalon et al.,[25] however, it was a clinical study and had a larger sample size. For this study, 47 patients were selected and provided 95 sites with cavitation. The results showed a specificity of ultrasound of 0.75 versus 0.9 for radiographs. The authors concluded that ultrasound exhibited a higher sensitivity than the radiographs but a lower specificity. The authors suggested that improvement in the ultrasound signal-processing algorithm could possibly reduce the number of false positives, resulting in higher specificity.

Dental fracture and cracks. Based on the same principle used to evaluate enamel thickness and carious lesions, ultrasound imaging can also be used to detect dental fractures and cracks at the dentinoenamel junction (DEJ). For this purpose, Culjat et al.[26] used a tooth phantom with acoustic properties similar to those of natural human enamel and dentin. A simulated crack was located at the DEJ. A 130 μm-thick transducer with a resonance frequency of 19 MHz was used. Despite the fact that crack reflections are extremely angle dependent, and the findings of this study were limited to planar cracks and interfaces oriented perpendicularly to the transducer, the study conducted was successful in distinguishing areas with and without simulated cracks.

Another study using a dental phantom was conducted by Singh et al.,[27] however, the authors' aim was to detect cracks in gold, amalgam and porcelain restorations. A 19 MHz transducer was used and the relative return echo amplitude from restoration surfaces was measured. The measurements were also made in extracted natural teeth. The results showed that cracks could be detected beneath porcelain and amalgam, and within a human molar. Cracks were not detected in simulated dentin beneath gold; however, simulated cement washout directly beneath gold was identified. This could be explained by the fact that gold restorations transmitted minimal acoustic energy due to their large acoustic impedance. The ability to penetrate resin-composite was also demonstrated. Promising results were also found by Dos Santos et al.,[28] who conducted their study on a human third molar tooth, using 10 MHz bandwidth ultrasonic instrumentation including a laser vibrometer and a 20 MHz contact piezoelectric transducer, in non contact mode.

Soft tissue lesions. Most dentists are unaware of the utility of ultrasound in the diagnosis of many types of oral diseases, and this may be disadvantageous to patients.[29] In light of this, Wakasugi-Sato et al.[29] demonstrated the clinical applications of ultrasound imaging in soft tissue lesions, guided fine-needle aspiration, measurement of tongue cancer thickness, and diagnosis of metastasis to cervical lymph nodes. Doppler ultrasound images were taken in the B-mode scan, with a 7.5-10 MHz linear array transducer. The Doppler mode in ultrasound was reported to be a useful modality in the differential diagnosis between normal and metastatic lymph nodes in patients with oral squamous cell carcinoma. The authors emphasized the importance of further investigations in this area, using standardized methods.

Friedrich et al.[30] described a case report in which ultrasound was used as an auxiliary tool, associated with radiography, to detect an adenomatoid odontogenic tumor. Ultrasound imaging was able to reveal the anterior surface of the tooth inside the lesion, indicating extreme thinning of the remaining cortical bone and liquid filling the cystic lesion.

Pallagatti et al.[31] conducted a clinical study in 45 patients to evaluate the efficacy of ultrasonography in comparison with clinical diagnosis, radiography and histopathological findings in the diagnosis of maxillofacial swellings. The ultrasound was equipped with color Doppler function, operating at a frequency of 8-12 MHz. After ultrasound imaging exams, the patients were subjected to histopathological examination to confirm the diagnosis. The diagnostic accuracy of ultrasound was found to be 92.3% in the diagnosis of cystic lesions, 87.5% in benign tumors, 81.8% in malignant tumors, 100% in lymphadenopathies and 90% in space infections and abscesses. The contingency coefficient of 0.934 was obtained when ultrasonography was compared with histopathology, which was highly significant. Significant results were obtained when ultrasonography was compared with clinical (0.895) and radiographic diagnosis (0.889). Radiography alone was not able to detect any case of lymphadenopathy, which was accurately diagnosed by ultrasound.

Head and neck swellings were evaluated by ultrasonography in 70 patients in a recent study conducted by Chandak et al.[32] The ultrasound features considered were shape, echo intensity, boundary, ultrasound architecture of lesion, posterior echoes, and ultrasound characteristic of tissues. A 15 MHz transducer was used. Intergroup comparisons were made between four different types of swellings: inflammatory; cystic; benign; and malignant. A comparison was made between benign and malignant neoplasms, and the criteria of boundary, echo intensity, and ultrasound architecture of lesions were statistically significant with $P \leq .05$. The comparison of inflammatory swellings and malignant neoplasms showed that the criteria of boundary and ultrasound architecture of lesions were statistically significant, also when benign neoplasms were compared with cystic and inflammatory swellings. The comparison of cystic swellings with inflammatory swellings and with malignant neoplasms, showed that the criteria of boundary, shape, echo intensity, posterior echoes, and ultrasound characteristics of tissues were statistically significant. The authors reported, on average, a higher accuracy and sensitivity of ultrasound imaging than in clinical diagnosis, confirming the importance of associating the clinical examination with ultrasonography.

Another clinical study was conducted by Yamamoto et al.[33] with 137 patients diagnosed with oral squamous cell carcinoma. After lesion excision, the patients were monitored for 1 year with ultrasonography (7.5 MHz transducer), computed tomography and magnetic resonance. Despite the limitations of the study, such as small sample; variables related to age, ethnicity, and sex; and the fact that culture data could not be obtained from all patients with stitch abscess, characteristic findings were demonstrated by ultrasonography, showing it to be a useful tool in the diagnosis of postoperative stitch abscesses.

Periapical lesions. Periapical lesions can be divided into periapical granulomas and periapical cysts; however, clinical examination, and radiographs alone are not able to differentiate between cystic and non-cystic lesions. In order to overcome this problem, new imaging techniques have been studied, including ultrasound.[34] Thus, Cotti et al.[34] used echography for the study of peri-radicular lesions. The study was conducted in 12 patients with periapical lesions of endodontic origin, diagnosed with conventional clinical and radiographic examination, and further examined using echography at the site of the diagnosed lesions. A multi frequency (7-9 MHz) ultrasound was used. By means of echography, it was possible to measure the lesions, evaluate their content and view their vascularization in different regions of the mouth in all cases. The results of this study demonstrated that echographic examination is a real-time imaging technique that has the potential for use in the assessment of periapical lesions. Subsequently, a similar study was performed by Cotti et al.[35] comparing differential diagnoses between periapical granulomas and cystic lesions. Once again, echography was able to reveal the nature of the content of bony lesions and helped in the differential diagnosis. The authors suggested that further studies should be conducted with regard to ultrasound imaging as a tool in the multiple differential diagnoses of bone lesions of the jaw.

Rajendran et al.,[36] also reported ultrasound to be an efficient tool for monitoring periapical lesions, using a 5-10 MHz frequency probe, in a case report with five patients. Color power Doppler was also used in the study. The limitation of the technique was the fact that color Doppler cannot penetrate and diagnose the presence of a periapical lesion unless there is a discontinuity or breach in the buccal bone plate. To circumvent these problems, a small intraoral probe would be helpful, in order to facilitate placement, especially in posterior teeth. Although the radiologist found difficulty in placing the probe intraorally, no discomfort was reported by patients during treatment.

Tikku et al.[10] evaluated the effectiveness of ultrasound, color Doppler imaging and conventional radiography to monitor the postoperative healing of periapical lesions of endodontic origin. Fifteen patients were selected for the study and the lesion characteristics such as size, shape, and dimensions were analyzed by both imaging techniques. This study showed that at 6 months, ultrasound and color Doppler imaging were significantly better than conventional radiography in detecting changes in the healing of hard tissue at the surgical site. The authors also affirmed that only ultrasound associated with Doppler can distinguish venous from arterial flow, quantify the amount of flow, identify the anatomy of feeding vessels and offer a visual demonstration of vascularity. The data presented indicated that ultrasound with color Doppler was an effective tool for monitoring the healing of periapical lesions after surgery.

Gundappa et al.[37] compared the use of ultrasound, digital, and conventional radiography in diagnoses of periapical lesions in 15 patients. An 8-11 MHz frequency transducer was used. The results showed that where sufficient buccal cortical bone had been resorbed, ultrasound imaging was straightforward but underestimated the size of the lesions when compared with periapical and digital radiography. Nevertheless, ultrasound provided accurate information on the pathological nature of the lesions.

Diagnosis of periapical lesions was also assessed in a study conducted by Aggarwal et al.[38] The authors compared computed tomography scans with ultrasound imaging, using power Doppler flowmetry. The echographic evaluation was performed with a 10 MHz frequency ultrasonic probe. In all 12 cases, the diagnosis with computed tomography scan and ultrasound coincided with the histopathological diagnosis of the lesions. It was concluded that computed tomography scans and ultrasound with power Doppler flowmetry can be used as additional diagnostic tools without invasive surgery. In addition, the authors affirmed that since the ultrasound diagnosis provide an accurate result, in the same way as the histopathological findings, it is a useful method for the diagnosis of periapical lesions, whether they are of endodontic or nonendodontic origin, and whether they are a granuloma or a cyst.[38] Similar results were recently reported in other studies,[39,40] confirming the use of ultrasound as an efficient tool to monitor and diagnose periapical lesions. Nevertheless, it is worth mentioning that ultrasound is still a supporting technique and may not substitute the traditional diagnosis methods, e.g., histopathology.

Maxillofacial fractures. Besides the fact that computed tomography (CT) and cone-beam CT (CBCT) are the most used methods to diagnose midfacial fractures,[41,42] ultrasonography has also been explored. Blessmannet et al.[41] analyzed the reliability of ultrasound in 10 patients with midfacial fracture in comparison with CT. An 8-12 MHz frequency was used for evaluation. One examiner ranked the ultrasound findings as regards the presence of fracture in six predefined anatomic landmarks on a scale from 1 to 5. In all but three patients fractures were correctly identified using ultrasound. In the remaining patients the examiner was unable to determine whether a fracture was present or not. Normally, these patients would have been subjected to conventional radiographs. It was concluded that ultrasound proved to be a reliable first-line imaging modality for the investigation of suspected midfacial fractures in daily clinical practice, resulting in decreased exposure to radiation.

Park et al.[43] conducted a study in 32 patients with suspected nasal bone fracture, in which ultrasonography and CT were used to evaluate the type and extent of the fractures. A 10 MHz broadband linear array transducer was used placed on the surface of the nasal bone, with the conductor used as an intermediary between the transducer face and the skin surface. Using real-time ultrasonographic images, bony fragments were repositioned by closed reduction and then again confirmed with real-time ultrasound. The authors reported that in a considerable number of cases, the remaining displacement was observed in ultrasonography, but not detected with palpation, resulting in further repositioning efforts, including revision of the position of the nasal bone. This study showed that ultrasonography was important and useful for evaluating and repositioning nasal bone fractures.

Nefazati et al.[44] compared ultrasound images with CT scans in zygomatic fractures in the 17 patients evaluated. A 7.5 MHz transducer, situated over the fractured arch transversely was used to evaluate its entire length. The results showed that ultrasound was accurate to assess the fractures with a sensitivity of 88.2% (15 of the 17 patients, with two false negatives) and a specificity of 100% (no false positives). It was concluded that ultrasound was accurate for visualizing zygomatic arch fractures and can be used as an adjunct to plain films to reduce overall exposure to radiation.

In a systematic review of the literature, performed by Adeyemo and Akadiri,[42] the diagnostic value of ultrasonography was described for assessment of maxillofacial fractures. Transducers with frequency ranging between 7.5 MHz and 30 MHz were used in the studies. The authors reported that isolated orbital floor fracture, especially from the posterior aspect, was not adequately visualized by ultrasound scans. The results showed the sensitivity and specificity of ultrasound in detecting orbital fractures were in the range of 56%-100% and 85%-100%, respectively, whilst those of nasal fractures were in the range of 90%-100% and 98%-100%, respectively, with high predictive values. Sensitivity or specificity of ultrasonography for detecting zygomatic fractures was higher than 90%. Studies on mandibular sub-condylar/ramus fractures showed a sensitivity and specificity in the range of 66%-100% and 52%-100%, respectively. As some of the advantages of ultrasound imaging, the authors cited the fact that it can be done in real-time, enabling dynamic and 3-D imaging; the equipment is portable enough to be moved into the operating room for intraoperative imaging and the evaluation of fracture reduction; and there is no risk associated with radiation, allowing imaging to be repeated several times without major concerns. Considering the several evidences presented in the literature, the use of ultrasonography in maxillofacial fractures can be justified, especially fractures involving the nasal bone, orbital walls, anterior maxillary wall and zygomatic complex. Thus, the sensitivity and specificity of ultrasonography are comparable with those of CT.

Periodontal bony defects. Ghorayeb et al.[6] conducted a review of the use of ultrasonography in dentistry. Among others, the authors cited the use of ultrasound for diagnosis of periodontal disease. The ultrasound energy reflected from the periodontal ligament is received by the transducer and the pulse-echo measurement was intuitively able to match the current method of periodontal probing. However, it results in a small echo because the acoustic impedance mismatch between the gingiva and the periodontal ligament is small. Unfortunately, due to the complexity of the periodontal anatomy and the small impedance mismatch, it continues to be difficult to precisely detect the periodontal ligament by means of this technique.

These data have also been confirmed by previous studies,[38,45] however, it seems that these problem could be circumvented, as recently reported by Chifor et al.[8] The authors evaluated reference points necessary to monitor horizontal bone resorption by means of ultrasonography with frequency of 20 MHz. The images were obtained by placing the transducer in a longitudinal plane in the lateral area of mandibular alveolar bone. These measurements were compared with those obtained from CBCT images and microscopy. The examinations were performed on the lingual side of the alveolar bone of four pig mandibles, in which the distance between the enamel-cementum junction and the coronal edge of cortical bone was measured, in order to identify the periodontal space, root and enamel-cementum junction. The authors concluded that in comparison with microscopy, ultrasound examination might be a reliable method to assess the periodontal system. Nevertheless, there has been a report of ultrasound being limited when visualizing the interdental septum. Due to the increased frequency of ultrasound, there is low penetration in the interdental area. So the authors have suggested that a miniaturized transducer could probably compensate this drawback, and the cementoenamel junction could be identified with high accuracy despite the convexities of tooth anatomy.[8]

With regard to the diagnosis of periodontal bony defects, Mahmoud et al.[11] recently conducted a study investigating the feasibility of using a custom-designed high-frequency ultrasound imaging system to reconstruct high-resolution three-dimensional surface images of periodontal defects in human. The system used single-element focused ultrasound transducers with center frequencies ranging from 30 to 60 MHz. The system was able to reconstruct 3-D images of the mandibular outer surface with superior spatial resolution and to perform the entire scanning procedure in less than 30 s. Major anatomical landmarks on the images were confirmed with the anatomical structures on the mandibles. All the anatomical landmarks were detected and fully described as 3-D images using this novel ultrasound imaging technique, whereas the 2-D X-ray radiographic images suffered from poor contrast. These authors reported that there is great potential for using high-resolution ultrasound as a noninvasive, nonionizing imaging technique for the early diagnosis of the more severe form of periodontal disease.

Tsiolis et al.,[46] in a study conducted in pig jaws, assessed the periodontium by means of ultrasonography, using a 20 MHz transducer. Three teeth per jaw were scanned with ultrasound, and then duplicate measurements were taken of the distance from a fixed landmark on the teeth to the alveolar bone crest. For the validation of the hard tissue measurements obtained by ultrasound, transgingival measurements were obtained, as well as direct measurements of the same sites after surgical exposure. Histological examination was also performed for a better understanding of the ultrasound image. This study demonstrated that ultrasonography can produce images at buccal sites suitable for assessment of the periodontium and accurate measurement of the dimensional relationship between structures. Statistical analysis of the measurements of certain fixed landmarks revealed that the ultrasonic scanner provided satisfactory results, both in terms of accuracy and repeatability.

In a literature review, Xiang et al.[17] summarized some of the diagnostic approaches, such as infrared spectroscopy, optical coherence tomography (OCT), and ultrasound. The authors reported that ultrasound imaging is able to visualize periodontal and oral tissues in vivo or ex vivo without the need for complicated processing, fixing, or staining. Furthermore, it is a fast and non-invasive method. The echography is described as an easy and reproducible technique with potential to supplement conventional radiography in the diagnosis and follow-up of periodontal diseases. The authors concluded that given the complex nature of periodontitis, it is improbable that only a single clinical or laboratory examination can address all issues concerning diagnosis and prognosis; moreover, non-invasive diagnostic methods seem to be the most promising candidates for these purposes.

Gingival thickness. For a precise diagnosis and in order to distinguish different structures, information on thickness of the masticatory mucosa is highly desirable. The information about mucosa thickness by means of a non-invasive method, such as ultrasound, would help diagnosis and treatment planning in several clinical situations.[47] Therefore, studies have been performed with the goal of designing an optimal ultrasonic device that should provide these data with accuracy.[47,48] However, as the acoustic properties of human gingiva have not yet been described, and due to some technical limitations concerning ultrasonography, such ultrasonic device continues to be a challenge to researchers.

Müller and Könönen[49] conducted a clinical study in 33 patients to measure gingival thickness by means of ultrasound. The transducer probe 4 mm in diameter was applied at the midfacial sites of each tooth, with light pressure to produce acoustic coupling. By timing the echo received with respect to the transmission pulse, the soft tissue thickness was determined within 2-3 s while transmitting an acoustic signal. The measurement was digitally displayed with a resolution of 0.1 mm and a minimum measurement of 0.5 mm. Periodontal probing depth and clinical attachment level were also assessed. Results showed that a 2-level (subject, tooth) variance component model of gingival thickness without any explanatory variable, revealed an intercept mean of 0.93 ± 0.02 mm. Subject variation of gingival thickness amounted to 4.2% of the total variance. Ultrasound was demonstrated to be useful for gingival thickness measurement.

Gingival thickness was also assessed in a study conducted by Savitha and Vandana[50] in 32 patients, at 338 sites, using an A-scan ultrasound probe. The authors compared the ultrasound measurements with the traditional method of transgingival probing. The mean gingival thickness in a midbuccal location was 1.08 for transgingival probing and 0.86 for ultrasound. For interdental papilla, the mean obtained was 1.26 and 0.77 for transgingival probing and ultrasound, respectively. The difference between the methods was found to be significant both in the mid-buccal and interdental papillary region, but the difference was insignificant at the mandibular canine and mid-buccal sites. It was concluded that both measurements were reliable in measuring the gingival thickness in a midbuccal location, whereas ultrasound measurements were not dependable in the papillary region.

Müller et al.[51] evaluated the degree of disagreement of ultrasound for measuring gingival thickness at different teeth. Gingival thickness was determined in 33 patients with plaque-induced gingivitis. Vestibular/buccal gingiva thickness was measured at the level of the gingival sulcus depth. The ultrasonic A-scanner was used with a frequency of 5 MHz. Unreliable measurements were largely confined to the maxillary and mandibular second and third molars. Error terms were lowest (0.03-0.05) at the maxillary canines and first premolars, and at the mandibular anterior teeth and premolars, where repeatability coefficients of 0.5-0.6 mm could be estimated. The authors concluded that performance of the device was best with certain tooth types with rather thin gingiva. Considering the rather large probe diameter of 4 mm, measurement resolution of 0.1 mm, and considerable disagreement of measurements found in this study, the minute increases in thickness in the micrometer range, which occurs during gingivitis, could hardly be detected by ultrasonography within the parameters used in this study.

With the same ultrasonic device (SDM, KRUPP Corporation, Essen, Germany; range of measurement 0.3-8.0 mm; resolution of 0.1 mm; frequency of 5 MHz; sensor diameter = 3.0 mm), a study was later conducted by Cha et al.[52] Area- and gender-related differences in the soft tissue thickness were evaluated in potential areas for inserting miniscrews in the buccal-attached gingiva and the palatal masticatory mucosa. In an evaluation of 61 adult patients (28 men and 33 women; mean age = 25.3 years; age range 19-35 years old), performed in the buccal-attached gingiva immediately adjacent to the mucogingival junction of the maxillary and mandibular arches, and 4 mm and 8 mm below the gingival crest in the palatal masticatory mucosa. The results showed that buccal-attached gingiva thickness in the maxillary arch was significantly greater in men than in women, but buccal-attached gingiva thickness in the mandibular arch and palatal masticatory mucosa thickness 4 and 8 mm below the gingival crest did not show gender differences. Significantly thicker soft tissue was found in the anterior areas in the maxillary arch and in the posterior areas in the mandibular arch. In the palatal masticatory mucosa, significantly thicker soft tissue was found 4 mm below the gingival crest in the anterior areas and 8 mm below the gingival crest in the posterior areas. The areas between the canines and the premolars showed higher values than other areas 4 mm below the gingival crest. However, the soft-tissue thickness 8 mm below the gingival crest showed a progressive increase from the anterior to the posterior regions. The authors concluded that the use of the ultrasonic device to measure soft tissue thickness could help practitioners to select the proper orthodontic miniscrew in daily clinical practice.

Muscle thickness. Ultrasonography has been described as being capable of providing uncomplicated and reproducible access to the parameters of jaw muscle function and interaction within the cranio-mandibular system.[53,54] This method represents a significant improvement over conventional methods to evaluate masseter thickness, especially in terms of clinical availability and cost.[53,54] Ultrasound examination is usually applied only to the superficial tissues in the maxillofacial region because the facial skeleton shields the deep tissues. However, it offers a potential advantage because it can be easily performed, is non-invasive and can be repeated several times.[53,55]

In a literature review conducted by Serra et al.[53] the authors discussed the advantages and disadvantages of using ultrasonography to assess the masticatory muscles. The authors reported that there were different techniques available for recording the thickness of the muscles, and that the ultrasound technique generally showed lower reproducibility in relaxed than in contracted muscles. They found that the masseter was the most common muscle studied, followed by the temporal muscle. Among the factors that may influence sizes measurements, the following were cited: age, gender, side of the muscle, bite force, weight, type of occlusion, occlusal contacts, temporomandibular disorder (TMD), ultrasonography and electrical activity of the masticatory muscles and facial morphology. The authors suggested that ultrasound should be preferred in comparison with CT and magnetic resonance imaging due to its safety and cost advantages, since it is as reliable and precise as those techniques.

Ariji et al.[56] conducted a clinical study including 25 women with TMD to assess masseter muscle thickness by means of ultrasound. Examinations were performed using a 12-MHz-wide bandwidth linear active matrix transducer (ranging from 6 to 14 MHz). The ultrasonogram was obtained with a focal range between 0.5 and 2.0 cm and an image depth of 6 cm. Echo gain and dynamic range were 26 and 69 dB. The visibility and width of the internal echogenic bands of the masseter muscle were also assessed and the muscle appearance was classified as 1 of 3 types: type I, characterized by the clear visibility of the fine bands; type II, thickening and weakened echo-intensity of the bands; type III, disappearance of, or reduction in number of the bands. The authors concluded that there would be a muscle thickness increment in patients with TMD. A similar study was later conducted by Ariji et al.,[57] with the aim of evaluating the efficacy of massage treatment in patients with TMD. In the 15 patients selected, ultrasonography was performed before and after treatment to measure the masseter thickness and to observe the existence of anechoic areas. The ultrasound method showed that in the unilateral group, masseter thickness on the symptomatic side significantly decreased after treatment.

In a recent study, Müller et al.[58] also assessed masseter muscle thickness by means of ultrasonography, using two different transducers, with a frequency of 6-8 MHz or 4-13 MHz. The authors showed that complete implant supported prostheses have positive effects on masseter muscle thickness, maximum bite force and chewing efficiency.

The ultrasound imaging has also been shown to be a useful tool to measure muscles thickness in the studies conducted by Kiliardis et al.[59] (7.5 MHz), Trawitzki et al.[60] (7.5 MHz), and Naser-ud-Din et al.[61] (5-13 MHz). These studies successfully assessed precise measurements and pointed out that diagnosis and follow-ups can be performed without repeatedly exposing patients to ionizing radiation.

Temporomandibular disorders. Magnetic resonance is at present considered the gold standard for visualizing the temporomandibular joint, as it allows representation of inflammatory changes in the joint space and positional abnormalities of the joint disk.[62,63] Nevertheless, magnetic resonance is restricted in the case of some patients, such as those with cardiac pacemakers, claustrophobia and metallic prostheses.[62,64] In addition, its use may be limited by its cost and the time it takes.[62] Ultrasonography is an alternative diagnostic method for imaging of the TMD, especially because high-resolution ultrasonography shows satisfactory results.[64] Moreover, ultrasonography is fast, comfortable for the patient, and less expensive, and is available in most centers.[64]

Manfredini and Guarda-Nardini[62] conducted a literature review on the accuracy and clinical usefulness of ultrasonography for the diagnosis of TMD. The accuracy of ultrasonography was found to be 54%-100%

for diagnosing disk displacement, 56%-93% for osteoarthrosis, and 72%-95% for joint effusion. In addition, the method seems to be operator-dependent. The authors emphasized that better standardization of the technique is required and normal parameters must be set. Nevertheless, ultrasonography continues to be potentially useful as an alternative imaging technique to monitor TMD.

High-resolution ultrasound was used in some investigations of the TMD.[63-65] In a study with 40 patients, Jank et al.[65] determined a correlation between the ultrasound diagnosis and the pathological clinical parameters of the TMD. Kaya et al.[63] and Çakir-Özkan et al.[64] also described the sensitivity of ultrasound in detecting anterior disc displacement. Despite the good results presented, one of the limitations of these studies was the lack of a second interpreter of the ultrasound images, which would have enabled a comparison of the interobserver variability.

Bas et al.[9] assessed the increased capsular width of the temporomandibular joint with high-resolution ultrasound, using a 10 MHz transducer, and a method similar to that used in the Manfredini et al.[66] study. The authors performed a receiver operating characteristic curve analysis to assess the most accurate cutoff value of capsular width that was able to discriminate between joints with and without magnetic resonance imaging (MRI)-depicted effusion. While Manfredini et al. revealed that the critical area is around the value of 2 mm for temporomandibular joint capsular width, Bas et al. revealed a value of 1.65 mm. The authors mentioned that this difference could be attributable to the difficulty of examination standardization. Furthermore, the major shortcomings of ultrasound is that accuracy mainly depends on the operator's training.[9]

Parra et al.[67] assessed the accuracy of a US-guided technique for visualizing needle placement within the TMD, in 83 children, in whom 180 TMD injections were performed. The ultrasound scanning procedure was performed with closed mouth, using a transducer (15-MHz linear or 8-MHz curvilinear) in a coronal plane and sweeping in a posterior direction along the zygomatic arch toward the TMD. CT was used to confirm diagnosis in 70% of the cases. The authors concluded that performing injections using ultrasound guidance was a safe, effective, and accurate procedure.

Aware of the drawbacks of ultrasound methods and the limited evidences presented in the literature as regards ultrasound sensitivity, Bas et al.[68] compared the results of the diagnostic parameters of ultrasonography and MRI in detecting TMDs using clinical diagnosis as the gold standard. A 10-MHz high-frequency transducer was placed over the temporomandibular joint perpendicular to the zygomatic arch in a transverse and longitudinal plane. Bilateral images were obtained in mouth-closed and maximal mouth-opening positions. The results showed that MRI presented a sensitivity of 85%, specificity of 62%, and an accuracy of 80% in the detection of internal derangements, against 69%, 80%, and 71% of ultrasonography, respectively. Poor reliability was found when the agreement between the MRI and ultrasound imaging diagnoses was compared. The authors suggested that with the use of devices with a frequency of $\geq$12 MHz, better visualization of joint structures and more reliable results with higher sensitivity and accuracy could be achieved.

Implant dentistry. Dental implant surgeries are often performed without incision and flap elevation in order to preserve gingival tissue and bone. Such approaches require accurate determination of tissue thickness. Moreover, determination of tissue thickness over implants is crucial for the selection of appropriate abutments, restorative components, and treatment planning. Implant location after healing is difficult, especially when implants are deeply submerged after thick connective tissue grafts. Radiographic assessment of healed implants only provides 2-D information, which may be difficult to accurately relate to the 3-D surgical site. Thus, ultrasonography may play an important role in locating submerged implants.[69]

Culjat et al.[69] developed a customized ultrasound imaging system, with a frequency of 16.1 MHz, to locate and measure the depth of implants submerged beneath soft tissue in a porcine model. Porcine muscle, with approximately 5 mm thick layers, was tightly adapted to the bony surfaces in order to simulate peri-alveolar soft tissue. Location of submerged implants was determined by measuring and comparing reflected power from the implant and bony surfaces. Based on this method, the implants were easily and accurately ($\pm$0.2 mm) located. The authors concluded that ultrasonic imaging, including a soft tissue matched transducer with a customized transceiver and signal processing, was capable of measuring soft tissue thickness over bone and implants placed in bone submerged beneath soft tissue in porcine models. The authors also mentioned that as the experiment was simulated in cancelous bone, cortical bone would be expected to have higher echo strengths because it has lower acoustic properties than cancelous bone. Therefore, it would be easier to measure tissue thickness over cortical bone, where implants are usually placed.

One of the major concerns of clinicians is the damage to the inferior alveolar nerve during implant surgery in the lower maxilla, especially at the posterior site. In the upper maxilla, special attention must be paid to the limits of the sinus floor during implant surgery or augmentation procedures. Thus, precision is important in surgical planning, and for this reason the CT and CBCT are the gold standard imaging modalities for providing accurate measurements and definition of details. Nevertheless, panoramic and intraoral radiography are commonly used to verify angular alignment and confirm the location of the osteotome and the dental implant in relation to these landmarks. These intraoral radiographs use additional radiation and often create more discomfort for the patient and clinicians. Hence, there is still a need for an accurate intraoperative device to precisely detect the distance from until the inferior alveolar canal and the floor of the maxillary sinus. Based on these needs, Machtei et al.[70] conducted a pilot study in 14 patients (21 implants) to intraoperatively measure the distance from the bottom of the osteotome to the inferior alveolar canal and maxillary sinus floor using a novel ultrasonic device and compared these measurements with conventional radiographs. Unfortunately, the authors did not provided information about technical specifications of this new ultrasound device, or the images generated. A drawback of this study was the fact that only one examiner performed all measurements, so the credibility and accuracy of the data could not be compared. The results showed that the mean radiographic distance from the apex of the pilot drill to the nearest cortical bone was 5.64-0.51 mm, and 5.22-0.37 mm for the ultrasound ($P = .34$). In posterior mandibles, the distances were 5.18-0.61 mm and 5.26-0.61 mm, for radiography and ultrasound, respectively, with no statistical difference between them ($P = .59$). A positive correlation was observed between the two measurements in mandibles ($r = 0.967$; $P = .0001$). The authors concluded that this new ultrasound device was efficient for intraoral measurements of the inferior alveolar canal and the floor of the maxillary sinus, as a diagnostic tool before dental implant placement.

There is still a lack of information in the literature, as regards ultrasound imaging in implant dentistry. Further in vitro and clinical studies are necessary in order to validate this technique and analyze its accuracy for precise planning of implant surgeries and follow-up.

CONCLUSIONS

Ultrasound imaging in dentistry has been increasingly developed and studied in recent years and it seems that this technology will gain even more space in dental practices. Nevertheless, most dentists are still unaware of the full utility of this technology. The findings of this study present some of the advantages of ultrasound in comparison to traditional modalities; such as non-ionizing radiation, non-invasive method, painless, accuracy, visualization of hard and soft tissue, and good acceptance by patients, which makes it very interesting and capable of being used in all specialties.

Ultrasonography may provide a significant benefit to patients by allowing early detection of tooth lesions and defects, measurement of mucosa and gingival thickness, dental implant locations, and dental scanning.

The data here presented are very promising with regard to the advancement of ultrasonography for dental scanning, diagnosis, and intraoral measures. Further studies should be conducted with the goal of achieving better quality and image resolution of ultrasound in imaging and diagnosis.

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