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ORIGINAL ARTICLE

Intraoral ultrasonography: development of a specific high-frequency probe and clinical pilot study

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Abstract Although ultrasonography is a non-invasive, inexpensive and painless diagnostic tool for soft tissue imaging, this technique is not currently used for oral exploration. Therefore, we developed a 25-MHz high-frequency ultrasound probe, specially designed for intraoral applications. This paper aims to present clinical intraoral ultrasound images actually interpretable, in order to identify the relevant applications of this novel tool and to design future oral studies. Two independent radiologists performed ultrasound examinations on three healthy volunteers. All the teeth were explored on the lingual and buccal sides (162 samples) to evaluate the ergonomics of the system and the visualisation of anatomic structures. Osseointegrated dental implants and a mucocele were also scanned. At the gingivodental junction of the maxillary and mandibular teeth, the device clearly identifies the tooth surfaces, the alveolar bone reflection with its surrounding subepithelial connective tissue of the gingiva and the gingival epithelia. The bone level and the thickness of soft tissue around the implant are measurable on the buccal and lingual sides. Therefore, intraoral ultrasonography provides additional morphological information that is not accessible by conventional dental x-rays. We propose a novel diagnostic tool that explores the biological width and is able to define the thin or thick nature of the gums. Moreover, intraoral ultrasonography may help to monitor precancerous lesions. This promising device requires large-scale clinical studies to determine whether it should remain a research tool or be used as a diagnostic tool for daily dental practice.

Keywords Ultrasonography · Periodontology · Implantology · Imaging · Probe

High-frequency ultrasound is a non-invasive, inexpensive and painless diagnostic tool commonly used in medical imaging. Ultrasonography is particularly indicated for the examination of soft tissues. In spite of that, this technique is not currently used for oral exploration, and few studies have been published on the subject [1–8].

Briefly, ultrasound is a cyclic sound pressure with a frequency greater than 20 kHz (greater than the upper limit of human hearing). Ultrasonic waves are produced by a piezoelectric transducer encased in a probe and propagate with a velocity that depends on the material (1,540 m/s in soft tissues). At the boundary between two tissues of different acoustic impedance, part of the energy of the incident pulse will be reflected and received by the same probe. When the impedance mismatch is important (as in soft tissue/mineralized tissue), the entire echo is reflected. The time of flight between the incident pulse and the reflected echo makes it possible to calculate the distance of this interface, because the speed of sound is constant. The attenuation limits the depth of exploration. Thus, increasing the frequency of ultrasound transmission improves image resolution, but decreases the depth of exploration. There is also a scatter effect in the tissue that leads to the emission of a fraction of the incident ultrasonic energy in all

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directions. The scattered echo will give the "echogenicity" of the tissues. The image is formed in real time by continuous scanning of the incident ultrasonic beam. The amplitude of the signal received by the probe is based on reflection, scattering and attenuation effects. Each image pixel is assigned a grey level function of the amplitude of the echo corresponding to its spatial location.

The devices previously described have been mostly adapted from borrowed ophthalmological or dermatological clinical instruments [9–19]. However, first, the probes used were not adapted to the oral cavity, so that the distal and lingual areas remained inaccessible [13, 14]. Moreover, the images were mostly obtained in an animal model, in controlled laboratory conditions, and the authors concluded that a miniaturized transducer would be necessary for ultrasound periodontal assessment in humans [16, 17]. Secondly, the probe frequency was insufficient to obtain high-resolution images, so that the interpretation of the complex anatomy of the periodontium remained difficult [18]. In summary, technological barriers limited the oral application of ultrasound. Recently, a 3D ultrasound imaging system for jawbone scanning able to detect different bony defects ex vivo has been described [19]. However, soft tissues were not studied. Other ultrasonic devices have been specifically developed to assess the depth of the periodontal pocket or the thickness of the gingiva, using pulse–echo measurement, which has good validity and reproducibility [20–27]. Ultrasound appeared as an attractive alternative to manual periodontal probing, since ultrasound is painless, non-invasive, repeatable and accurate. But these early devices operate in mode A (amplitude modulation) and provide only quantitative information, without displaying images.

To overcome these shortcomings, we developed an ultrasound brightness-mode (B-mode) prototype, which operates with monitoring and uses a 25-MHz high-frequency ultrasound probe specially designed for intraoral applications. This paper aims to present the first intraoral ultrasound images actually interpretable, in order to identify the relevant applications of this tool and to design future oral studies.

Materials and methods

We used intraoral ultrasonography, which is composed of a custom probe linked with an image processor and an electronic platform. This probe has been shaped as a dental hand piece to be easily moved in the mouth, and it allows full assessment of the oral mucosa and periodontium (Fig. 1). This probe is composed of an electronic input/output control, a motorization group and a chamber of transducer enclosed in the intraoral head.

Fig. 1 Ultrasound device prototype, probe shaped as a dental hand piece and PZT transducer

The transducer is a 3.6-mm-diameter single lead zirconate titanate ceramic (PZT) block immersed in a coupling liquid inside the chamber (15×18 mm) closed by a 0.2-mm 8BK membrane. The scanning frequency motion of the transducer is 10 Hz with 75-μm axial and radial resolution. Our approach has been to focus the spot of ultrasound beam more superficially, to optimise the periodontal soft tissue imaging.

The specifications of the PZT transducer are listed below:

- Dimensions of the pseudocylindrical transducer: external active diameter, 3.6 mm; overall dimensions: diameter, 5 mm; height, 4.2 mm
- Radius of curvature (front face), 8 mm
- Central frequency, 20 MHz
- Other improvable frequencies, 16 and 25 MHz with an acceptable attenuation
- 20 MHz focal distance, 7.7 mm
- 20 MHz field depth (−6 dB), 2.4 mm
- Lateral resolution, 165 μm
- Axial resolution, 75 μm
- Pulse length (−20 dB), 130 ns
- 22 MHz impedance, 25±5 Ω
- Transducer sensibility for a single 22 MHz sinus pulse (16 Vpp, 50 Ω), 425 mV

In accordance with the ethical committee guidelines, two independent radiologists performed 25-MHz ultrasound examinations on three healthy volunteers (aged 22, 33 and 59 years) without periodontal disease. All the teeth were explored on the lingual and buccal sides (162 samples) to evaluate the ergonomics of the system. Five-year-old osseointegrated dental implants and a mucocele on the lower lip have also been scanned. The probe was first positioned at the junction between the tooth and gum. A commercially available ultrasonic gel coupling was interposed between the probe tip and the tissue surface, in order to exclude air and to ensure good contact. The dynamic sequences of acquisition were recorded, and metric evaluations between the tissue interfaces were secondarily performed from screenshot. The intraoral image samples were then observed by the radiologists who had to rate them for detectability of anatomic boundaries (visualisation of bone level, marginal gingiva and mucogingival line). The inter-rater agreement was statistically measured using Cohen's kappa coefficient. The soft tissues around the implants were also explored as well as the salivary cyst before surgical excision.

Results

Preliminary clinical trials show good-quality ultrasound images enabling distinction of the anatomic boundaries of peri-dental soft tissues, alveolar bone level, gingival epithelium and oral mucosa. The exploration is performed from surface to depth as shown from left to right in Figs. 2, 3, 4, 5, 6 and 7. Following millimetric abscissa axis, the first millimetre corresponds to the internal chamber of the ultrasound probe uniformly filled with a coupling liquid. The first echo of the external membrane of the probe appears at 1 mm (Figs. 2 and 3). Coupling gel is interposed between this membrane and the biological tissues and looks like a hypoechoic area with a few noises consistent with the heterogeneity of the colloidal gel. Overall, if the probe can be positioned properly (more than 92% of cases), the distinction between soft and mineralized tissues is clear. Table 1 shows the visual detectability rate of the anatomic boundaries obtained by each radiologist. The high frequency of 25 MHz provides high resolution compatible with the limited depth of exploration required. The pilot study on a limited patient sample shows that tooth surfaces are well depicted at the gingivodental junction of the maxillary and mandibular teeth, along with a good visualisation of the limits of the alveolar bone and surrounding subepithelial connective tissue of the gingiva (Table 1, Figs. 2 and 3). The almost total reflection echoes of mineralized tissue mask the root surfaces covered by dental alveolar bone, but the morphological boundary provides good visualisation of the bone level in more than 90% of cases. Consequently, the periodontal biological width between the marginal gingiva and alveolar bone level is identifiable and measurable. The tissue-reflected signals vary with the keratinised nature of the epithelium (gum or mucosa) and may reflect the epithelial projection in connective tissues (epithelial rete pegs). The keratinized gingiva reflection appears to have a distinct echogenicity compared to the mucosa, which allows positioning of the mucogingival line in about 80% of cases. In instances of anatomical cementoenamel junction gap, the ultrasound can objectify the cementoenamel junction. Overall, the magnitude of the kappa coefficient reflects a very good inter-observer agreement.

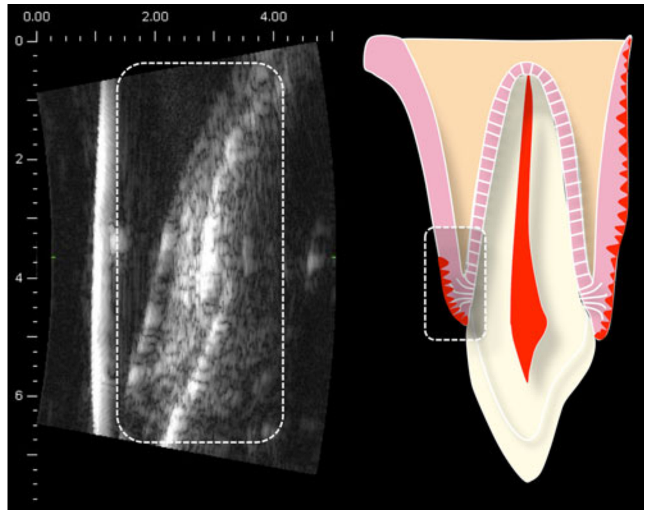

Fig. 2 Twenty-five megahertz ultrasound image (7×5 mm window) of a maxillary canine periodontium (buccal side). The *dotted frame* shows the positioning of the probe on the sulcus. Ultrasonography appears as a longitudinal section of the tooth and its periodontium

The images shown are frames from a dynamic sequence of ultrasound acquisitions so that the pulse noise is then maximum and could affect the resolution of anatomic details. The interface between two tissues does not appear perfectly smooth, and these discontinuities increase when the US beam is not perpendicular to the studied plane. The dynamic exploration in real time reduces this artefact by visual frame averaging. Moreover, multiple reflection echoes produced into interfaces with high acoustic impedance mismatches (as mineral-

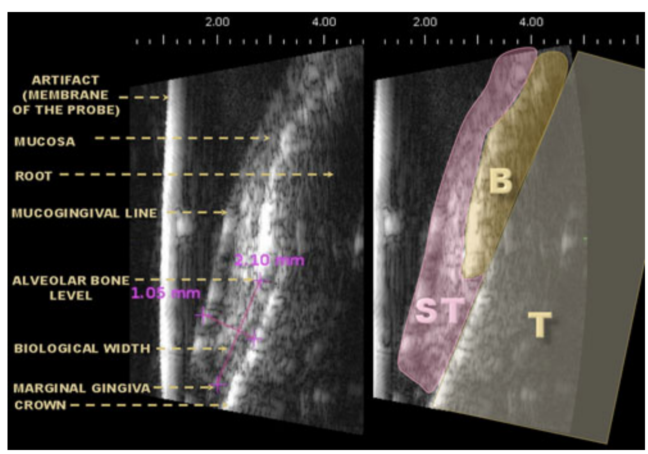

Fig. 3 Same image with legends and matching with bone (*B*), soft tissues (*ST*) and tooth (*T*) areas. The surface of the tooth roots and alveolar bone are hyperechoic compared to soft tissue. The keratinized gingiva reflection produces a different ultrasound signal compared to the mucosa. The thickness of soft tissues and the biological width can be measured

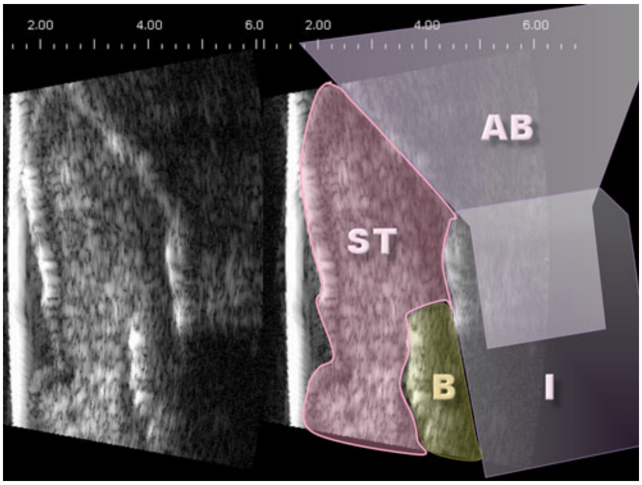

Fig. 4 Peri-implant exploration (25 Mhz, 7×5 mm window) matching with bone (*B*), soft tissues (*ST*), abutment (*AB*) and implant (*I*) areas

ized tissue/soft tissue boundaries) might lead to rough measurements (bone thickening).

Similarly, as regards implantology, the bone level and the thickness of soft tissue around the implants are measurable. The connection between prosthetic abutment and artificial titanium root is visible (Figs. 4 and 5).

Imaging palatal regions leads to measuring the thickness of the potential donor site for subepithelial connective tissue graft

Fig. 5 Same spot with the clinical and angulated x-ray views. Note that the ultrasound measurement between the bone and the implant abutment junction is consistent with the measurement on dental radiography (1.6 mm)

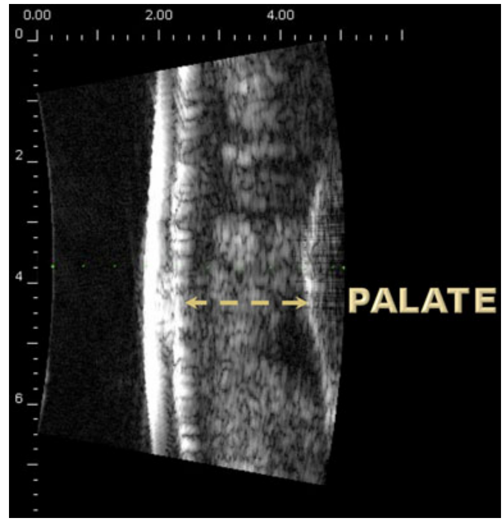

Fig. 6 Palatine exploration before mucogingival surgery for root coverage

or to choosing a suitable orthodontic anchorage screw (Fig. 6). Some anatomical features are apparent provided they are superficial: incisive and palatine foramina, bone fenestration, superior and inferior labial arteries, ranine veins, etc.

The exploration of the lower lip ultrasound confirms the thick liquid contained in the mucocele (salivary cyst),

Fig. 7 Clinical view and ultrasonography of a mucocele of the lower lip

Table 1 Ergonomics of the probe and detectability rates of anatomic boundaries observed by two independent radiologists on 162 intraoral samples (81 for marginal gingival and mucogingival line)

	Correct positioning of the probe for interpretable images (%)	Visualisation of bone level (%)	Visualisation of marginal gingiva (%)	Visualisation of mucogingival line (%)
Radiologist 1	92.6	90.1	92.6	85.2
Radiologist 2	93.8	90.7	93.8	79

When the positioning of the probe is correct, the marginal gingiva can always be spotted. The magnitude of the kappa coefficient reflects almost perfect inter-observer agreement to obtain a correct positioning of the probe for interpretable images (κ=0.90, p<0.05) and to distinguish the bone level (κ=0.97, p<0.05) or the marginal gingiva (κ=0.90, p<0.05). The concordance remains substantial for the visualisation of the mucogingival line (κ=0.79, p<0.05)

which is well encapsulated (Fig. 7). The diagnosis was confirmed by histology.

Because of the small size of the probe and its special dental design, patients felt the oral ultrasonography was a stress-free, painless and rapid examination: less than 1 min for each area of interest with minimum operator training.

Discussion

We propose a novel diagnostic tool for exploring intraoral soft tissues. The ultrasound should explore not only the intraoral mucosa but also the periodontium, i.e. the tissues supporting the tooth corresponding to the gums, alveolar bone and periodontal ligament. In fact, periodontal diseases are infectious diseases that are common causes of tooth loss and may affect cardiovascular diseases, diabetes, or increase the risk of preterm birth [28–33]. Diagnostic and follow-up of the oral cavity are actually performed by clinical examination, radiology and photography [34]. These techniques give practitioners satisfying information, but do not allow them to detect periodontitis in the early stage. 3D reconstructions using cone-beam CT x-ray might hold potential with regard to the periodontal bone loss assessment during pre-surgery examination but would imply a radiation dose too large to be acceptable for follow-up in the periodontal disease [35, 36]. As optical coherence tomography (OCT) and near infrared spectroscopy (NIR), ultrasonography is a novel non-invasive approach for periodontal diagnosis [37, 38] without any discomfort for the patient during the procedure and does not use ionizing radiation. By scanning a focused light beam across the tissue surface, OCT imaging has been compared to ultrasound scanning. As ultrasonography, OCT reveals microstructural details of the periodontal soft tissues and offers the potential for determining attachment level and identifying active periodontitis. However, the loss of coherence caused by scattering within the sample limits the penetration depth to 2 mm in biological tissues. Based on tissue oxygenation measurement, NIR can be used to monitor multiple inflammatory indices (hemodynamic and oedema-based markers) to identify early signs of inflammation leading to soft tissue breakdown but does not allow morphological images.

This project aimed to create a high-resolution ultrasonography system which provides an instantaneous and atraumatic cross view of the periodontium, in order to accurately appreciate and monitor periodontal diseases.

This fine tip similar to a dental hand piece is suitable for use in the oral cavity and to explore the periodontium of almost all teeth. The qualitative assessment of images led to an initial description of the echogenicity of the periodontium: the surface of the tooth root, the alveolar bone, all the peri-dental soft tissue, the cementum–enamel junction and other elements such as anatomical foramina or the labial artery. The distances between the boundary tissues are easily and directly quantifiable. The good inter-rater agreement shows that the technique seems slightly operator dependent. Intraoral ultrasonography provides additional morphological information inaccessible by conventional dental x-rays, such as the thickness of soft tissue or the bone level of the buccal and lingual sides. This intraoral probe can measure the biological width and define the periodontal biotype, i.e. the thin and thick nature of the gums, which is a significant predictor of the periodontal outcome [39].

The prevention of cancer of the upper airway includes a systematic review of the oral mucosa. Intraoral ultrasonography may help to monitor precancerous lesions in combination with biopsy. Lodder et al. [40] have shown that tumour thickness measured with an ultrasound intraoperative transducer is an important predictive marker for lymph node metastases. Ultrasound imaging is used to estimate tumour size and to define adequate resection margins [41]. This novel high-resolution and easily moving probe could assess deep infiltrations more accurately.

We first wanted to test the feasibility and usability of an intraoral probe. This prototype provides purely morphological images and does not have a colour-Doppler velocimetry function. It would be interesting to describe the inflammation of periodontal lesions and search for neoangiogenesis in oral mucosa lesions. Technically, the field of exploration is limited to 8 mm in the coronoapical direction, which may be too low to visualise deep periodontal pockets. A coupling device such as an ultrasonic gel pad might be developed to increase the contact between probe and tissue. In addition, for the more distal exploration (wisdom teeth), the ergonomics could be improved. Similarly, the positioning of the probe on the lingual side of the mandibular incisors is not easy enough. Moreover, it will be necessary to standardize the examination through a placement system of the ultrasound probe.

Conclusion

As it is atraumatic and without ionizing radiation, ultrasonography may be repeated frequently to monitor the stability of therapeutic interventions (mucogingival plastic surgery, marginal bone loss at peri-implant sites) dynamically and in real time, quantitatively and qualitatively. Ultrasonography offers new prospects for periodontal phenotyping (gum thickness), prevention (earlier detection of a small anatomic change), diagnosis and therapeutic monitoring of periodontal diseases and oral mucosa lesions. The periodontal biological width is directly accessible and measurable. This promising device needs large-scale clinical studies to validate its diagnostic value and determine whether it should remain a research tool.

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Conflict of interest The authors declare that they have no conflict of interest.

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