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Non-ionizing Real-time Ultrasonography in Implant and Oral Surgery: A Feasibility Study

Hsun-Liang Chan, D.D.S., M.S.[*], Clinical Assistant Professor, Hom-Lay Wang, D.D.S., M.S., Ph.D.[*], Director and Professor, J. Brian Fowlkes, M.S., Ph.D.[**/***], Professor, William V. Giannobile, D.D.S., M.S., D.M.Sc.[*/***], Chair and Professor, and Oliver D. Kripfgans, Dipl. Phys., Ph.D.[**], Research Associate Professor

*Department of Periodontics and Oral Medicine, University of Michigan School of Dentistry, Ann Arbor, MI, USA.

**Department of Radiology, University of Michigan Medical School, Ann Arbor, MI, USA

***Department of Biomedical Engineering, College of Engineering

Corresponding author:

Oliver D. Kripfgans, Ph.D.

Department of Radiology and Department of Biomedical Engineering, University of Michigan,

1301 Catherine St. Medical Sciences I, Room 3218D, Ann Arbor, MI 48109-5667

TEL: (734) 647-0852

E-mail address: oliver.kripfgans@umich.edu

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Abstract

Purpose: Ultrasound imaging has potential to complement radiographic imaging modalities in implant and oral surgery given that it is non-ionizing and provides instantaneous images of anatomical structures. For application in oral and dental imaging, its qualities are dependent on its ability to accurately capture these complex structures. Therefore, the aim of this feasibility study was to investigate ultrasound to image soft tissue, hard tissue surface topography and specific vital structures. **Material and Methods:** A clinical ultrasound scanner, paired with two 14 MHz transducers of different sizes (one for extraoral and the other for intraoral scans) was used to scan the following structures on a fresh cadaver: (1) the facial bone surface and soft tissue of maxillary anterior teeth, (2) the greater palatine foramen, (3) the mental foramen, and (4) the lingual nerve. Multiple measurements relevant to these structures were made on the ultrasound images and compared to those on cone-beam computed tomography (CBCT) scans and/or direct measurements. **Results:** Ultrasound imaging could delineate hard tissue surfaces, including enamel, root dentin and bone as well as soft tissue with high resolution (110 µm wavelength). The greater palatine foramen, mental foramen and lingual nerve were clearly shown on ultrasound images. Merging ultrasound and CBCT images demonstrated overall spatial accuracy of ultrasound images, which was corroborated by data gathered from direct measurements. **Conclusion:** For the first time, this study provides proof-of-concept evidence that ultrasound can be a real time and non-invasive alternative for the evaluation of oral and dental anatomical structures relevant for implant and oral surgery.

Key words: Ultrasonography, Dental Implants, Bone Regeneration, Alveolar Ridge, Anatomy, Cone-Beam Computed Tomography

Introduction

Understanding the location, size, shape and spatial relationships of dental and oral structures is essential for clinicians to plan and execute surgeries. During the past decade, cone-beam computed tomography (CBCT), owing to its ability to replicate anatomy accurately in 3 dimensions, has greatly supplemented the use of two-dimensional (2D) conventional dental radiographs (Chan, et al. 2010, Loubele, et al. 2007, Ludlow, et al. 2007). Although a single CBCT scan delivers low-dose radiation, repeated scans on the same patient is not advisable (e.g., during a surgery to avoid injuring vital structures) (Horner, et al. 2009). Furthermore, CBCT is not applicable for evaluating peri-implant structures due to beam hardening and scattering artifacts (Gonzalez-Martin, et al. 2015, Kuhl, et al. 2015).

Non-ionizing, real-time and less expensive ultrasound imaging is extensively used in quantitative medical diagnostics for evaluating fetal tissue dimensions for several decades (Hadlock, et al. 1991). The ultrasound scanner transmits high-frequency ultrasonic pulses, between 1 and 20 MHz in general, into the region of interest with a transducer that both transmits and receives such pulses. Based on time of travel of ultrasound pulses and their received pressure amplitudes, the scanner displays a grayscale image depicting the tissue distance from the ultrasound transducer and the tissue's echogenicity (reflectivity) with respect to the original pulses. Although not able to reasonably penetrate bone with the current diagnostic imaging frequencies, ultrasound can delineate bone surface explicitly, providing an adequate morphological depiction of the bone (Backhaus, et al. 2001, Barratt, et al. 2006, Blankstein 2011, Cardinal, et al. 2001). Because of this unique feature, it has been gradually adapted in orthopedics for diagnosing bone fracture and bone diseases that erode/invade bony surfaces (Backhaus, et al. 2001, Barratt, et al. 2006, Blankstein 2011, Cardinal, et al. 2001).

In Dentistry, ultrasound imaging is mainly used as a research tool for dental diagnosis, such as evaluating tooth structures ((Bozkurt, et al. 2005, Culjat, et al. 2003, Hughes, et al. 2009, Slak, et al. 2011), soft tissue lesions ((Chandak, et al. 2011, Friedrich, et al. 2010, Pallagatti, et al. 2012, Wakasugi-Sato, et al. 2010, Yamamoto, et al. 2011), peri-apical lesions (Aggarwal, et al. 2008, Cotti, et al. 2003, Cotti, et al. 2002, Gundappa, et al. 2006, Rajendran & Sundaresan 2007), periodontal bony defects (Chifor, et al. 2011, Mahmoud, et al. 2010, Tsiolis, et al. 2003), gingival thickness (Muller, et al. 2007, Muller & Kononen 2005), and for implant-related applications (Culjat, et al. 2008, Machtei, et al. 2010), etc. However, it can potentially become a chair-side imaging modality during implant and oral surgery, in addition to the use of other radiographs because it reveals unprecedented soft tissue contrast and hard tissue surface topography in cross-sectional views. Recent technological advances have resulted in smaller transducers, which can accelerate the acceptance of ultrasound imaging in the dental community for intraoral applications. Therefore, this proof-of-principle study aimed to determine if ultrasound can image some specific oral and dental landmarks that are important for performing oral surgical and implant related procedures.

Materials and Methods

This is a non-regulated study, as determined by the University of Michigan Institutional Review Board (Study ID: HUM00107975).

Specimen acquisition and ultrasound equipment

A fresh 85-year-old male cadaveric head was used in this study. The specimen was kept frozen at -20℃ until the initiation of the experiment. One examiner (OK), who specializes in ultrasound imaging controlled the scanner, and one periodontist (HC) guided the ultrasound probe. A clinical ultrasound scanner (ZS3, Zonare, Mountain View CA, USA) was used and paired with a 14 MHz linear array transducer (L14-5w) for extraoral scans and a 14 MHz intraoperative array transducer (L14-5sp) for intraoral scans (Figure 1). To obtain well-resolved bone edges, a specific function on the scanner, named spatial compounding was selected. Suitable signal-to-noise, as anticipated in oral soft tissue imaging, allowed for the selection of a dynamic range of 80 dB for large soft tissue contrast. Acoustic coupling for conduction of sound waves was achieved with the application of ultrasound gel and the use of gel-based stand-off-pads. The anatomies of interest were (1) the facial alveolar bone surface and mucosa of maxillary anterior teeth, (2) the greater palatine foramen, (3) the mental foramen, and (4) the lingual nerve.

Placement of the transducer

1. Scans of anterior maxilla: The transducer was placed at the midline of the teeth mesio-distally, approximately following their long axes. Both extraoral and intraoral scans were performed.
2. Scans of the greater palatine foramen: The transducer was placed at the intersection of the palatine and alveolar process of the maxillary bone, slightly distal to the 2nd molar, where the foramen is most commonly located (Fu, et al. 2011). The transducer was then moved anteroposteriorly and apicocoronally in small increments until the foramen could be seen.
3. Scans of the mental foramen: The transducer was placed extraorally with its long axis approximately parallel to that of the 1st and 2nd premolar. The transducer was then moved anteroposteriorly and tilted faciolingually until the

foramen and facial surface of the tooth and alveolar bone could be clearly imaged.

4. Scans of the lingual nerve: The transducer was first placed at the lingual side of the mandibular 2nd molar at the level of the alveolar crest apicocoronally ( ). The transducer was then moved along the surface of the lingual mucosa until the nerve was revealed in the image.

Images were saved in standard clinical Digital Imaging and Communications for Medicine (DICOM) format. The ultrasound image contrast was optimized, a process called windowing, using imaging software (ImageJ, National Institutes of Health, Bethesda, MD) for comparison to CBCT. The threshold was selected so that the edge of the structure, e.g. hard tissue surfaces with strong ultrasound echoes, was sharpened on the image for better identification.

CBCT scanning

The specimen was scanned by an experienced operator using a CBCT scanner (3D Accuitomo 170, JMorita, Japan), with scanning parameters of 120 kVp, 18.66 mAs, scan time of 20 seconds, and resolution of 200 µm. A cheek retractor and cotton rolls were used to delineate facial mucosa from gingiva/alveolar mucosa. The captured CBCT scans were three-dimensionally reconstructed with the built-in software and saved in DICOM format, and subsequently exported into commercially available software (Invivo5, Anatomage Dental, San Jose, CA, USA). The cross-sectional slices corresponding to the ultrasound scan images were saved and compared to the ultrasound images.

Preparation of gross anatomy

After ultrasound and CT scans were performed, a full thickness facial flap was raised to reveal the facial bone surface in the maxillary anterior region (Figure 2) and the mental foramen in the mandibular premolar region. Cross sections of the anterior teeth along with their surrounding tissues were prepared with a powered handsaw and photographed. Soft tissue overlying the greater palatine foramen was excised to visualize and measure the foramen. The lingual was dissected following a technique described in a previously published article (Chan, et al. 2010) for a direct measurement of its dimension.

Quantitative analysis

The following linear measurements were made by one calibrated examiner (HC) on ultrasound images and compared to those on CT images and/or direct measurements on the specimen: (1) the distance between the bone crest and the cemento-enamel junction (CEJ) and (2) the mucosa thickness at 5 mm from the CEJ on the facial side of all maxillary anterior teeth, (3) the mesio-distal diameter of the greater palatine foramen, (4) the mucosal thickness over the foramen, (5) the distance between the superior border of the mental foramen and the alveolar crest, (6) the diameter of the mental foramen, and (7) the diameter of the lingual nerve. Mucosal thickness on the cadaver was measured with a caliper (IWANSON spring caliper for wax, Hu-Friedy, Chicago, IL, USA) accurate to 0.1 mm. Other direct measurements were made with a periodontal probe (the University of North Carolina (UNC) Probe, Hu-Friedy, Chicago, IL, USA) accurate to 1 mm. Mean values of measurements (1) and (2) were calculated by averaging the readings from the 6 maxillary anterior teeth.

Results

Results of the measurements are summarized in the Table. The mean distance between alveolar crest and cementoenamel junction measured by ultrasound is 4.3±1.1 mm, compared to 4.6±0.4 mm and 4.1±0.9 mm for CBCT and direct readings, respectively. The mean anterior mucosal thickness is 0.3±0.1 mm on ultrasound images; while the corresponding CBCT and direct readings are 0.5±0.1 mm and 0.3±0.1 mm, respectively. Anatomical findings on 2D ultrasound images in relation to CT images and gross anatomy are described below.

Maxillary anterior region with intraoral ultrasound scan

The enamel surface closer to the CEJ, the root surface between the CEJ and the alveolar crest, alveolar bone surface, and the overlying mucosa could be identified (Figure 3). The enamel, root dentin and bone surface are hyperechoic because of strong sound reflection from these surfaces. The shadow under the hyperechoic tooth and bone surface is an artifact due to ultrasound's strong reflection on hard surfaces. The multiple parallel white lines under the enamel surface (Figure 3) may be related to the internal structural layers of the tooth, yet their spatial distance is not calibrated due to the higher speed of sound in the enamel (5,500 m/s) and dentine (3,600 m/s) when compared to the soft tissue (1,540 m/s). The size and spatial relationships of the aforementioned external structures are aligned with those in CBCT images (Figure 3 and Table).

Maxillary anterior region with extraoral scan

In addition to depicting structures in the vicinity to the tooth that could also be seen in intraoral scans, extraoral scans can reveal the vestibular depth and different muscle layers, orientations and their insertions to the maxilla within the lip (Figure 3F). The facial concavity of the maxilla is shown on the ultrasound scan.

Greater palatine foramen, mental foramen and lingual nerve

The greater palatine foramen is characterized by a discontinuity of the hyperechoic bone surfaces (Figure 4A). The greater palatine bundle could be visualized in the canal. Like the greater palatine foramen, the mental foramen is a discontinuity of the facial mandibular bone surface (Figure 4D). Additionally, this extraoral ultrasound scan displayed the depth of the vestibule, gingiva/mucosa around the premolar, enamel, root and bone surfaces, the buccinators m. and the depressor muscles of the mandible. The lingual nerve was presented as a hyperechoic structure in the lingual submucosa by the cortical surface of the mandible (Figure 4H). As it extends upwards in the parapharyngeal space, its course was shown as a hypoechoic ovoid.

Discussion

This pilot study demonstrates the feasibility of ultrasound to evaluate multiple important oral and dental anatomical structures. Tissue biotype is considered an important determinant to manifestation/treatment outcomes of periodontal diseases (Chao, et al. 2015, Fu, et al. 2010), and esthetic risk of dental/implant therapy (Lin, et al. 2014). Various methods have thus been developed to evaluate tissue biotype, with probing and visual assessment being the most commonly applied methods (Kan, et al. 2010). Ultrasound has been used for this purpose with high accuracy (Muller, et al. 2007, Muller & Kononen 2005). However, the scanners used in the literature often only display readings of mucosal thickness, not images (Muller, et al. 2007, Muller & Kononen 2005). Displaying images is advantageous because it is both more visual and more informative for the purpose of planning surgeries and comparing treatment outcomes. In addition to providing static measurements, ultrasound images might show blood flow and elasticity of oral mucosa, which could prove critical for designing flaps and determining the healing potential of bone/soft tissue regenerative procedures (Chao, et al. 2015).

This pilot study demonstrates the feasibility of ultrasound for identifying the greater palatine foramen, mental foramen and lingual nerve. Therefore, ultrasound-guided anesthesia, which has been gaining popularity medically (Neal, et al. 2010), might be useful for facilitating block anesthesia of these nerves more efficiently. Current techniques for applying local anesthesia use anatomical landmarks to locate targeted sensory nerves. Anatomical variation of nerve location can result in ineffective anesthesia. Multiple attempts to apply local anesthetic agent might increase systemic toxicity. The greater palatine nerve might be mislocated by up to 4 mm in a cadaver study because of variations in the vault height and the thickness of palatal mucosa (Fu, et al. 2011). The mental foramen, although often palpable clinically, could be misdiagnosed, especially in patients with severe alveolar ridge resorption. Additionally, ultrasound might reduce the incidence of injuring these important structures during surgery, especially in a minimally invasive surgery.

This project was not designed to quantitatively validate the accuracy of ultrasound images; nevertheless, the size and spatial relationships of the anatomies on ultrasound images agreed with CBCT scans and direct measurements. The facial alveolar crest of the maxillary anterior teeth is, on average, approximately 4 mm apical to the CEJ, measured with the three methods. The mean facial mucosal thickness is in a range of 0.3 to 0.5 mm for all three methods. Future studies with a larger sample size are underway to compare these measurements between ultrasound and CT images and the direct measurements for quantitative validation. Furthermore, the accuracy of ultrasound to determine other clinically relevant parameters, e.g. the degree of facial concavity of the maxilla (Chan, et al. 2014) and the buccal plate thickness (Fu, et al. 2010), should also be evaluated.

The limitation of ultrasound imaging is that structures within bone could not be seen, such as the inferior alveolar nerve. Therefore, some types of radiographic image would still likely be required. Additionally, a medium is required for sound transmission. Challenges of widely applying ultrasound imaging to oral surgery are (1) efforts to develop a system optimized for oral scanning, (2) equipment costs, (3) a learning curve for surgeon to read and interpret ultrasound data, (4) openness of ultrasound equipment manufacturers to this new indication, and (5) acceptance of this novel modality to the dental community.

Conclusions

This study demonstrates the feasibility of ultrasound for imaging oral soft tissue, hard tissue surfaces and specific vital structures. Therefore, ultrasound has significant potential to aid surgeons in “visualizing” oral structures during minimally invasive surgery and guide local anesthesia for difficult cases. Validation of this imaging modality in a more extended population with different bone and soft tissue densities will be required before implementation to clinical practice.

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Tables and Figures

Anatomical	Maxilla	Mandible

location	Anterior		Posterior		Posterior		
Parameter (mm)	BC-CEJ Mean±SD (Median)	MT Mean±SD (Median)	GPF-d	MT-GPF	MF-d	AC-MF	LN-d
Ultrasound	4.3±1.1 (4.1)	0.3±0.1 (0.3)	5.8	6.3	3.8	16.4	2.3
CBCT	4.6±0.4 (4.6)	0.5±0.1 (0.5)	6.7	6.5	3.7	16.9	N/A
Direct	4.1±0.9 (4.0)	0.3±0.1 (0.3)	N/A	N/A	4.1	16.0	2.5

Table: Comparisons between ultrasound, cone-beam computed tomography and direct measurements.

KEY: CBCT: cone-beam computed tomography measurements; Direct: direct measurements; BC-CEJ: the distance between alveolar crest and cementoenamel junction; MT: mucosal thickness at 5 mm apical to CEJ; GPF-d: diameter of the greater palatine foramen; MT-GPF; mucosal thickness over greater palatine foramen; MF-d: diameter of mental foramen; AC-MF: the distance between alveolar crest and MF; LN-d: diameter of lingual N. N/A: not assessed (N=6 for anterior specimens and 1 each for posterior specimens)

Figure 1: Ultrasound scanner and transducers used in this study. The scanner is equipped with a display, a control panel and a central processing unit. Two transducers with frequency of 14 MHz were used for extraoral and intraoral scans, respectively.

Ultrasound scanner

Extraoral transducer

Intraoral transducer

Figure 2: Frontal view of the maxillary anterior teeth before and after full-thickness flap elevation. The buccal plate is thin. The distance between CEJ to the bone crest is 4.1±0.9 mm. The mucosal thickness at 5 mm apical to the CEJ is 0.3±0.1 mm.

Figure 3: Intraoral and extraoral ultrasound scans of maxillary anterior teeth. The colored and windowed ultrasound image is to highlight hard tissue surfaces that are hyperechoic. A merged image is to show match of the spatial relationship of dental anatomy. On the ultrasound image, the surfaces of enamel, root dentin and alveolar bone are clearly delineated. Additionally, the soft tissue layer, including alveolar mucosa, submucosa and muscle layers can be seen. On the extraoral ultrasound image, the surfaces of enamel, root dentin and alveolar bone are also clearly delineated. The labial concavity apical to the root apex can be seen with this extraoral scan. Additionally, the soft tissue layer, including the lip, alveolar mucosa, submucosa and muscle layers can be seen. (CEJ: cementoenamel junction) (Scale bar= 5 mm)

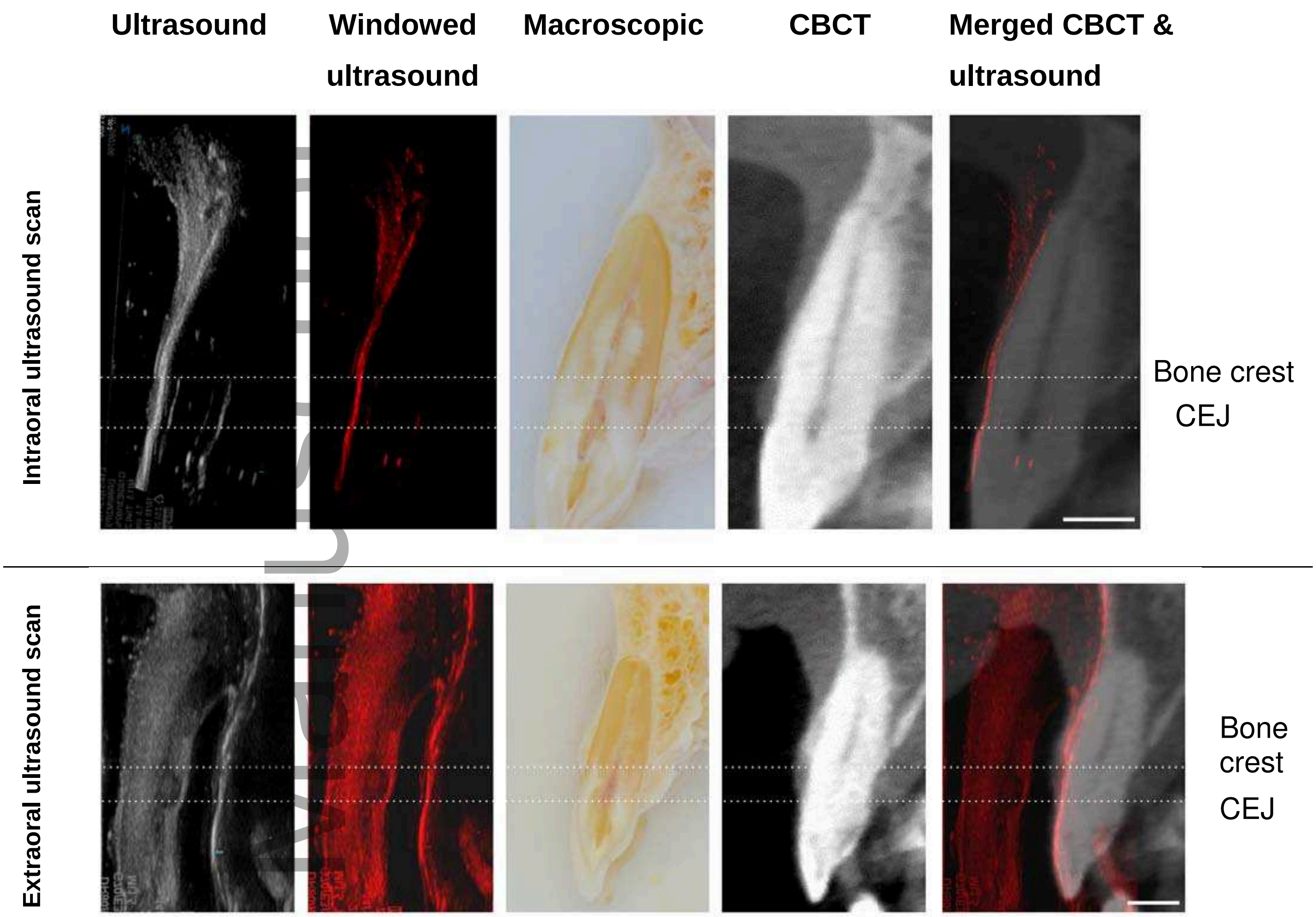
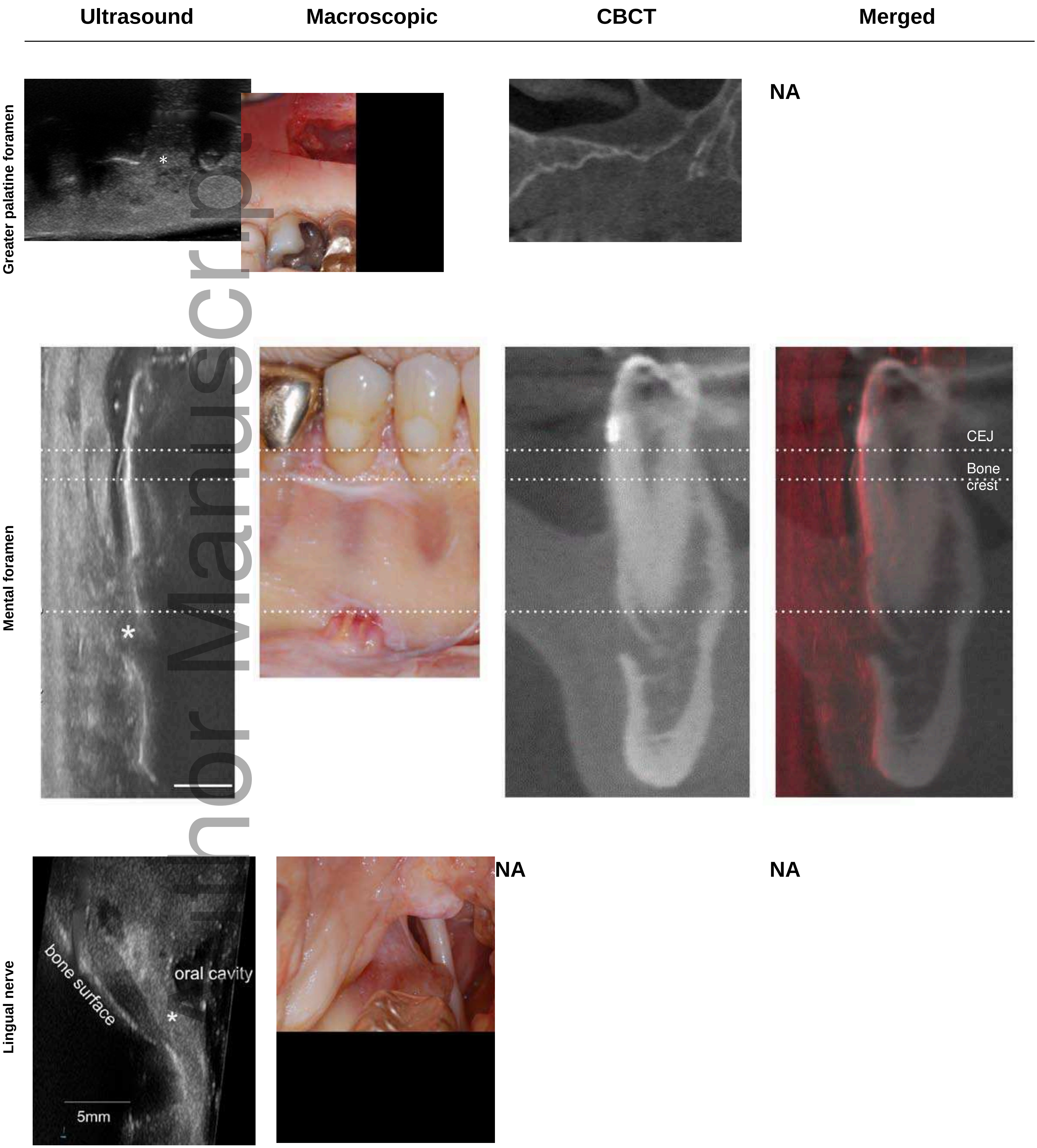


Figure 4: An image composite including images of the greater palatine foramen, the mental foramen, and the lingual nerve. The greater palatine foramen and the mental foramen are shown on the ultrasound image as a discontinuity of the bone surface. The ultrasound image including the mental foramen also presents a clear delineation of the surface of enamel, root dentin, alveolar bone and the mucosal layer. The merged images demonstrate an overall spatial registration of ultrasound and CT image, suggesting the accuracy of ultrasound images for mapping the surface topography of oral anatomy. The lingual nerve (asterisk) is shown as a hyperechoic structure lying next to the lingual side of the mandible, shown as a hyperechoic line. (CEJ: cementoenamel junction; NA: not available) (Scale bar= 5 mm)



Ultrasound
Macroscopic
CBCT
Merged
Greater palatine foramen
*
NA
Mental foramen
*
CEJ
Bone crest
Lingual nerve
bone surface
oral cavity
*
5mm
NA
NA