■ RADIOLOGY

Introduction to Through-Transmission Alveolar Ultrasonography (TAU) in Dental Medicine

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ABSTRACT: Through-transmission alveolar ultrasonography (TAU) is a novel imaging modality in dental medicine. A brief introduction to through-transmission ultrasonography (TTU) is followed by a description of the first commercially available TAU device, the Cavitat CAV 4000 (Cavitat Medical Technologies, Inc., Alba, TX). Recent associations between systemic osteoporosis, oral osteoporosis, periodontal diseases, and cardiovascular diseases underline the importance of early detection and treatment of oral cancellous bone pathologies associated with low bone density (LBD), such as regional ischemic osteoporosis, chronic nonsuppurative osteomyelitis, bone marrow edema, and cavitational ischemic osteonecrosis (osteocavitation). While the impact of osteoporosis on maxillofacial bones is acknowledged, there is a lack of reliable prevalence rate, and the National Institutes of Health (NIH) recommend that more attention should be paid to skeletal health, especially in persons with conditions known to be associated with secondary osteoporosis. TAU, a safe and effective imaging modality, can be a valuable tool in research as well as for the clinical assessment of alveolar cancellous bone pathologies associated with LBD and ischemia.

Ultrasound imaging technology, a safe and minimally invasive procedure, has been in use in medicine since the 1940s. This well proven modality is used to examine many parts of the body. Most commonly, pulse-echo ultrasound is used during the first, second, or third trimester of pregnancy. The American Institute of Ultrasound in Medicine indicates that the prudent use of diagnostic ultrasound for medical indications offers benefits that outweigh any risks that may be present, even in obstetrics. In spite of this, its use in dental medicine has been limited and mainly restricted to soft tissue applications such as parotid gland pathologies.[1] More recent research has focused on potential applications of ultrasound for caries detection,[2,3] imaging of the TMJ,[4-6] gingival thickness assessment in periodontology,[7] mandibular fracture evaluation,[8] and imaging of the cancellous portion of the maxillary and mandibular bones. Some investigators have been able to assess, to a certain degree, osteolytic lesions of the mandible, and even periapical infections, with pulse echo-sonography.[9,10]

In pulse-echo ultrasonography, the imaging capability is entirely dependent on reflected sound. The ultrasound wave pulsed by the transducer is reflected back to the

source, which also works as a receiver. The ultrasound wave characteristics are analyzed and converted into an image displayed on a monitor. Since a bone\soft tissue interface is highly reflective, a high fraction of the ultrasound is reflected, converted into heat by absorption or scattered by bone. This causes what is called an acoustic shadow, as structures in or behind the bone surface cannot be imaged by using conventional pulse-echo, B-mode grey-scale imaging.

Thus pulse-echo ultrasound, as used in other medical fields, has been of little diagnostic value for imaging the medullary portion of bones, hence it's limited use in dental medicine where imaging of calcified tissues is of primary importance.

Through-transmission ultrasonography (TTU), however, does not rely on reflected sound waves for imaging. In TTU, the system will only measure the acoustic wave going through a given medium instead of the echo being reflected back at the transducer.

The reflective method, also known as pulse-echo ultrasonography, has been the modality of choice in medical imaging since the 1940s. However, the past decade has seen a resurgence of TTU with the development and commercial introduction of a number of through-transmission systems.

Through-transmission ultrasonographic imaging of the cancellous portion of the alveolar bone as an aid to assessing alveolar cancellous bone density and quality is the focus of this article.

Display Modes

There are various types of displays for ultrasound imaging. Presently the only TTU device commercially available for imaging the alveolar bone is the Cavitat Ultrasonograph CAV 4000 (Cavitat Medical Technologies, Inc., Alba, TX) which uses a modified C-Mode display and is defined as through-transmission alveolar ultrasonography (TAU).

Unlike the B-Mode, which is a 2D display of a tissue section along the propagation axis of the beam, C-Mode is a plane view of a slice of the specimen perpendicular to the ultrasound beam axis (**Figure 1**). C-Mode can be used in pulse-echo or through-transmission. In the through-transmission mode, the image contrast is derived primarily from differences in attenuation and/or time of flight of the ultrasound wave as it passes through the entire specimen.[11] Until recently it was used mainly in non-destructive type testing in industry.

The Cavitat CAV 4000 uses a 2D color display (**Figure 2**) that is extrapolated as a 3D view (**Figure 3**) that can be rotated or magnified by the operator.
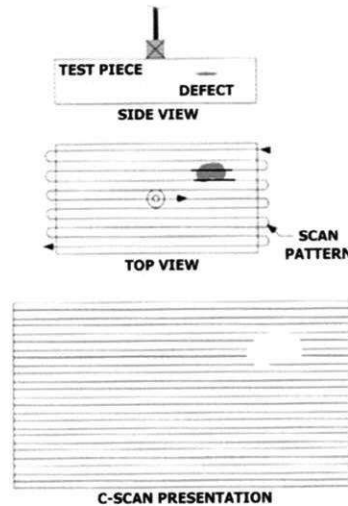

Figure 1
Schematic representation of C-Mode.

Tissue Types

The characteristics of ultrasound are closely related to the media which can be broadly divided into gas, liquid and solid. Tissues, because of their high liquid content,
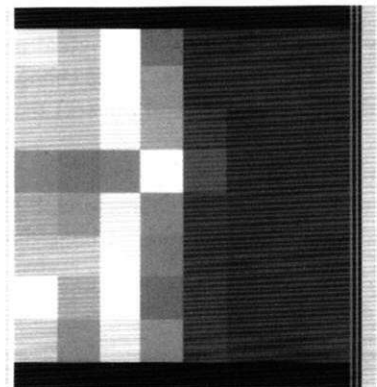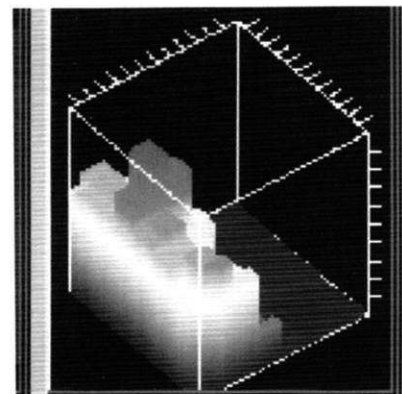

Figure 2 (above) 2D T Scan.

Figure 3 (below) 3D T Scan.

can be considered liquids. Because biological tissues are heterogenous, the propagation of ultrasound varies according to tissue type (**Table 1**).

Of particular interest in TAU is fat, cortical and cancellous bone. Cortical bone is the thick external layer of the alveolar ridge encapsulating the cancellous part. Of the two, cancellous bone is the more complex tissue. From an acoustical point of view, it is far from an "ideal medium," since it consists of an anisotropic, heterogenous open-celled framework of mineralized tissue saturated in marrow fluid. Normal cancellous bone, including jawbone, consists of moist, relatively dense, relatively uniform and highly connected trabeculae.[12-15]

The specific region of interest in TAU is the alveolar process which is integrated into the maxillary and mandibular body. It is defined as the part of the maxilla and the mandible that forms and supports the sockets of the teeth. Anatomically, no distinct boundaries exist between the body of the maxilla or the mandible and their respective alveolar processes. The marrow spaces in the cancellous bone of the alveolar process may contain hematopoietic marrow, but they usually contain fatty marrow.[16]

As complex as healthy cancellous bone can be, it is even more complex in a pathological state. The level of complexity depends on the pathological nature of the changes in the cancellous bone. These changes can affect both the calcified structure and the soft tissue marrow.

Osteoporosis

Osteoporosis is a disease characterized by low bone mass and structural deterioration of bone tissue, leading to bone fragility and an increased susceptibility to fractures, especially of the hip, spine, and wrist. It is generally categorized as primary (idiopathic) or secondary, depending on the absence or presence of associated medical conditions, surgical procedures or medications known to be associated with accelerated bone loss.[17] Secondary osteoporosis is sometimes a purely local phenomenon, confined to particular bones or parts of them.[18]

Osteoporosis is a different disease from osteomalacia. It results from abnormal organic matrix formation rather than abnormal bone calcification. In general, in osteoporosis, the osteoblastic activity is less than normal, and consequently the rate of bone deposition is depressed. Multiple factors can be involved, including but not limited to, lack of use of bones, malnutrition to the extent that sufficient protein matrix cannot be formed, deficiency in vitamin C (which is apparently necessary for the secretion of intercellular substances by all cells including osteoblasts), postmenopausal lack of estrogen secretion (estrogens have an osteoblastic stimulating activity).[19] The increase in venous thromboembolism related to HRT must also be evaluated when estrogen replacement is considered in osteoporosis.[20] A recent study concluded that estrogen plus progestin increases the risk of ischemic stroke in generally healthy postmenopausal women. Excess risk for all strokes attributed to estrogen plus progestin appeared to be present in all subgroups of women examined.[21] Ischemia can also have deleterious effects on bone mineralization.[22,23]

The diagnosis of osteoporosis is complicated by the fact that osteoporotic bone loss cannot be detected by ordi-

Table 1
Typical Ultrasound Velocity, Characteristic Acoustic Impedance and Attenuation in Different Biological Tissues for Temperatures Between 20C and 37C. These Values Based on Published Data by Wells[39] and Njeh[83] Are Only Indicative Due to Biological Variability

Tissue	Ultrasound propagation velocity V (m/s)	Characteristic acoustic impedance Z (10^6 kg m^{-2}s^{-1})	Slope of attenuation coefficient (dB cm^{-1} MHz^{-1})
Water	1480 (20° C)	1.48	0.002
Air	340 (20° C)	0.00044	1.2
Blood	1566	1.66	0.2
Cancellous bone	1450-1800	-	10 - 40
Cortical bone	3000-4000	4.0 - 8.0	5
Fat	1450	1.38	0.6 - 0.8
Liver	1560	1.65	0.6 - 0.9
Muscle	1550-1660	1.65 - 1.74	0.5 - 3.5
Skin	1600	1.6	2.4

nary clinical examination, even with the help of routine blood tests or x-rays.[24] Thus, special investigations using the most modern methods are necessary. TAU is such a method.

Velocity of Sound and Cancellous Bone

Velocity of sound in cancellous bone has a definite linear correlation with density.[25,26] Velocity is a good indicator of bone density loss caused by such factors as thinning of the trabecular network, found in primary osteoporosis, and loss of trabecular structure, found in more severe forms of osteoporosis such as ischemic osteoporosis and osteonecrosis.[27-29]

Attenuation of Sound and Cancellous Bone

Attenuation of sound in cancellous bone does not have a linear relationship with density.[30] The strongest correlation between attenuation and density exists at lower density and only over a limited density range.[31] In the published literature, explanations for this nonlinear behavior center around the role of scattering and absorption.[25,31,32] Since the data has been almost exclusively qualitative, there is a need to develop a more detailed understanding of attenuation in cancellous bone, because factors other than bone density are involved.

Bone Marrow and Ultrasound Transmission

A number of studies have looked at the influence of bone marrow on ultrasound. Alves,[33] who measured bovine cancellous bone at one MHz, found an increase in velocity of 2.9% when bone marrow was replaced by water, but a decrease of 8.8% in specific attenuation under the same conditions. In human cancellous bone, Nicholson[34] found that marrow decreased velocity and increased attenuation compared to water saturated bone. Of particular interest is the fact that bone marrow seems to have a proportionally greater effect on attenuation than velocity.

Cancellous Bone—The Role of Ischemia in Osteoporosis and TAU

Osteoporotic trabecular bone is characterized by relative dehydration, trabecular thinning, trabecular disruption (loss of connectivity, loss of continuity), and irregularity in the calcified structure.[35]

Under ischemic conditions, numerous pathological changes in the bone marrow and trabeculae of oral cancellous bone have been documented. Microscopically, areas of "apparent fatty degeneration and/or necrosis, often with pooled fat from destroyed adipose cells (oil cysts) and with marrow fibrosis (reticular fatty degeneration)" are seen. These changes are present even if "most

bony trabeculae appear at first glance viable, mature, and otherwise normal, but closer inspection demonstrates focal loss of osteocytes and variable micro cracking (splitting along natural cleavage planes)." "The microscopic features are similar to those of ischemic or aseptic osteonecrosis of long bones, corticosteroid-induced osteonecrosis, and the osteomyelitis of caisson (deep-sea diver's) disease."[36]

In the cancellous portion of the femoral head, it is not uncommon to find trabeculae with apparently intact osteocytes which seem to be "alive" but are no longer synthesizing collagen.[37] This appears to be consistent with the findings in alveolar cancellous bone.

Collagen in trabecular bone, or lack thereof, has also been shown to have a greater effect on attenuation than velocity. Hoffmeister, et al., reported in decollagenized cancellous bone specimens, an increase in attenuation of between 35 and 77% compared to a decrease in velocity of 10 to 12%. In demineralized specimens the increase in attenuation was between 44 and 58% and the decrease in velocity of 19-39%.[38]

In theory, the formation of areas of pooled fat (oil cysts) in diseased bone marrow should have a relevant influence on acoustic behavior. The available data seems to point in that direction. Fat itself is significantly more attenuating than water while velocity is only slightly less in fat than water (**Table 1**). Thus a higher concentration of fat in a specific area of medullary bone should have a greater effect on attenuation than velocity.

Since ischemically damaged cancellous bone will exhibit significant degenerative marrow changes before any easily detectable structural changes in the trabecular structure, the effects of such changes on ultrasound transmission need to be further studied.

Another factor is specular reflectance due to the smooth surfaces of steatocytes and oil cysts which will further attenuate acoustic energy. While velocity is a good indicator of cancellous bone mineral density, as discussed earlier, could attenuation be a better indicator of qualitative changes such as degenerative marrow changes in the absence of any significant structural alteration of oral cancellous bone? A hypothesis that remains to be proven.

Njeh, et al.,[26] raised this very issue of the distinct abnormality of ultrasound wave propagation in low density cancellous bone stating that further studies were clearly needed to find an explanation. One possible explanation that we propose is that while low density bone can be simply the result of thinning of the trabecular structure with a healthy bone marrow content, it can also be the result of a more severe pathological process in which loss of bone density occurs only in the later stages

of the disease and is preceded by a pathological degeneration of the bone marrow content as a result of ischemia[37-39] and/or other known or unidentified oral and/or systemic factors.

Through-Transmission Ultrasonography (TTU) Devices

As mentioned previously, a number of TTU devices, called Quantitative Ultrasound System (QUS), are now commercially available. All the QUS devices are designed as bone densitometer including through-transmission alveolar ultrasonography (TAU).

These systems have been developed mainly for use in medicine as an alternative to ionizing radiation for assessing bone mineral density (BMD). Loss of bone density, or osteoporosis, a significant medical problem in the human population, is usually diagnosed based on information obtained with x-ray based devices such as quantitative computed tomography (QCT) and single or dual energy x-ray absorptiometry (SXA-DXA), which is relatively expensive and bulky medical imaging devices that have the disadvantage of using ionizing radiation.

In most dental offices, bone density and quality is assessed using intraoral radiography and/or orthopanto-mography, which are excellent imaging tools when cortical damage is involved, but have been shown to have significant limitations when cancellous bone is concerned.[40-45] Although recent advances in digital radiography have enhanced radiographic imaging, the limitations regarding cancellous bone imaging[24] as well as the dangers of ionizing radiations are still an issue. Thus, additional imaging modalities are required to assist dental clinicians in their effort to measure oral BMD, changes in trabecular bone density/quality and to detect oral osteoporosis, especially since an association between reduced BMD and periodontal status has now been established and there is evidence that patients with systemic osteoporosis are likely to have decreased oral bone density as well.[46,47]

TAU and the Cavitat Ultrasonograph CAV 4000

The TAU device, the Cavitat Ultrasonograph CAV 4000, was developed by engineers at Cavitat Medical Technologies. It became commercially available in February 2002 and uses ultrasound attenuation (UA), time of flight (TOF), and a third proprietary method of signal analysis to assess medullary bone quality and density.

The device is based on a frequency of 2.5 MHz. The inventors have found this frequency to be optimal for penetration through alveolar bone. The acoustic wave is pulsed at a rate of 27,000 per ms via a proprietary flat piezoceramic transducer with an acoustic intensity of 0.4mW/cm². These parameters are significantly different from other commercially available devices. For example, reflective devices will use a repetition rate of between 1000 to 5000 times per second and most manufacturers of QUS devices use a lower range of ultrasound frequencies, ranging from 0.25 to 1.25 MHz.

The display includes a simulated oscilloscope showing the percentage of maximum amplitude of the acoustic wave in it's y axis and time in ms on it's x axis. The operator can observe the rate of attenuation of the wave in real time.

Attenuation is measured as the signal strength of the acoustic wave against the intraoral sensor array which is made up of 64 individual transducers bonded to a square piezoelectric membrane. The transducers convert the energy of the acoustic signal into a microelectrical signal analyzed by an AMD central processor and proprietary software to display a 2D and 3D color image. Information from each transducer of the sensor array is displayed as a square in the 2D view and as a vertical column in the 3D view. Each exposure represents the average of at least eight separate acoustic pulses against each of the 64 transducers of the array. The total image is made up of 64 squares/columns. The image is color coded to display 256 levels, or units, of attenuation and the height of each column is linked to the level of attenuation. Normal bone is imaged as dark green and increasingly attenuated bone is represented by light green, yellow/green, yellow (moderate loss), orange, orange/red, and red (most severe attenuation). Accordingly, maximum column height is associated with dark green (256 units) and minimum column height with dark red (six units).

The colors displayed are nonlinear and a color palette is always visible on the screen for immediate reference while reading the image (**Figure 4**).

According to the manufacturer, it is the lack of connectivity and thickness of trabeculae that determine signal strength (attenuation) and therefore, the height of the three-dimensional column display.

The patent on which the Cavitat CAV 4000 is based and the FDA 150K market approval indicate attenuation as the mechanism of action. In addition, the manufacturer explains that TOF is used to localize intra-medullary areas of LBD (personal communication with Cavitat Medical Technologies, 8/25/03). TOF is displayed on the x axis of the oscilloscope. Thus, TOF is the measure of the time taken, in microseconds, by the acoustic wave to travel through tissues, from the extra-oral transducer to the intraoral sensor array:
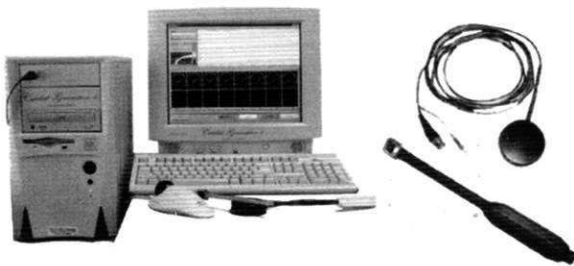
$$TOF = d/V_u$$

Figure 4
Nonlinear color palette.

Where d is the distance between the transducer and sensor and Vu is the velocity of ultrasound per square millimeter.

The Cavitat Ultrasonograph CAV 4000 is a pulse-transmission ultrasonic imaging device specifically designed for imaging the cancellous bone inside the alveolar ridges of the maxillary and mandibular bones (**Figure 5**).

Scanning Technique

A food-grade coupling gel (aloe vera) is applied to the extraoral transducer (emitter) to insure good acoustic conductivity and is placed on the facial skin of the patient. Gel may also be applied intraorally in the buccal sulcus to insure continuous acoustic contact between the buccal mucosa and the gingival tissues, especially in cases where the anatomical contour of the buccal aspect of the ridge is conducive to air bubble entrapment. The incoming ultrasound waves are received by the digital sensor array which is imbedded in the tip of a rigid wand, so careful positioning of the tip relative to the extraoral transducer and the alveolar ridge is important. A sterile transparent plastic sleeve is filled with coupling gel and positioned over the tip and any bubbles inside the gel must be carefully extruded. Gel is also applied on the tip once the sleeve is in place to insure good acoustic conductivity. The tip is positioned intra-orally on the lingual or palatal surface of the alveolar ridge, parallel to the extraoral transducer and the alveolar ridge. The goal is to have a perpendicular path of entry of the acoustic wave into the alveolar ridge so as to minimize refraction (**Figure 6**).

The process of TAU imaging is known alternatively as a Cavitat Scan, a TAU Scan or τ Scan. A "recall" button allows the operator to access stored 3D data from previous τ Scans (**Figure 7**). The information on the monitor can be printed as a form which also includes patient details. A copy can be provided to the patient immediately following the τ Scan (**Figure 8**).

As with any new imaging technique, the scanning procedure and image interpretation requires training and a certain amount of skill as placement of the sensor and transducer in relation to anatomical structures is very important. Hence, this is a user sensitive technique and the above instructions are a simple introduction. Training is definitely required and should be provided by professionals who have expertise in TAU as well as in the relevant clinical sciences.

TAU Grading

A grading system based on a histopathological confirmation of 285 scanned alveolar sites has been developed for the Cavitat Ultrasonograph and presented to the FDA as part of the approval process.[51,52] As explained previously, each column is divided into 256 units of attenuation displayed in a nonlinear color scale. The green range represents a column height of 129-256 units, while yellow represents a column height of 91-128 units, brown of 75-90 units, orange of 65-74 units and red of 6-64 units. As described in **Table 2**, the grading system is designed to classify the degree of alveolar cancellous bone attenuation so as to facilitate image interpretation and treatment planning.

Figure 5
Cavitat Ultrasonograph with extraoral transducer and intraoral digital sensor array.
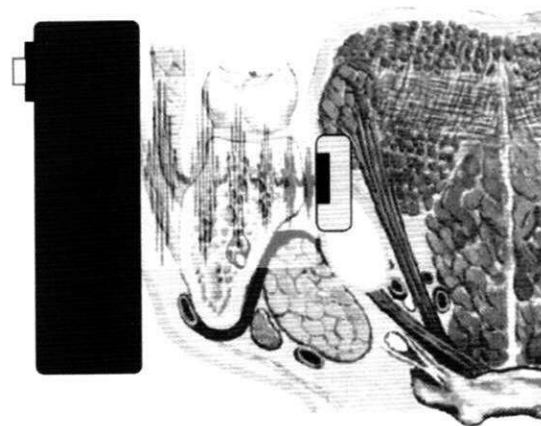
Figure 6
Proper positioning of transducer and intraoral sensor array.
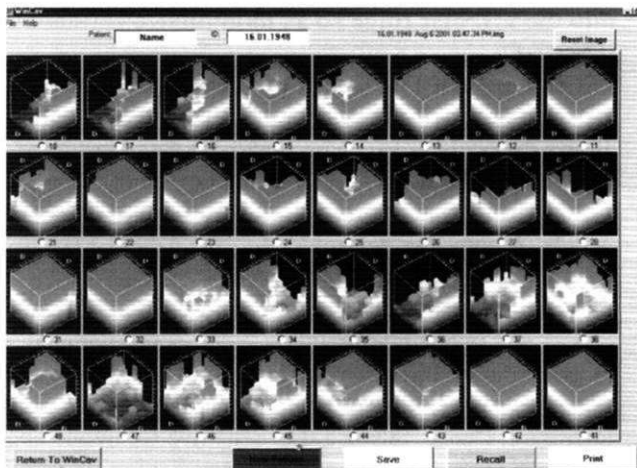
Figure 7
3D data display of all four quadrants.
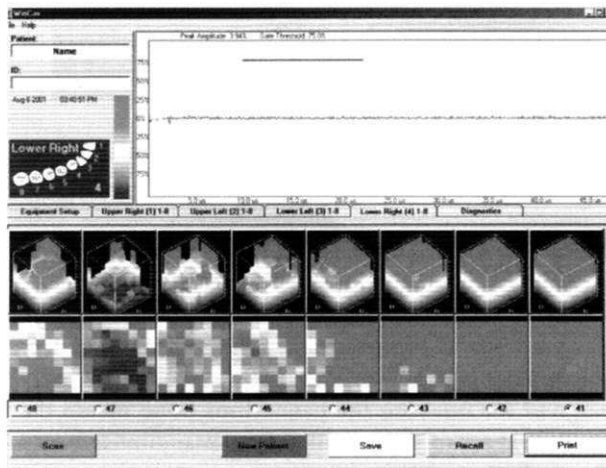
Figure 8
Information as displayed on the Cavitat CAV 4000 LCD screen.

At present, based on available clinical evidence, it is suggested that only high grade (grade III & IV) lesions should be considered for conservative surgical exploration in the absence of very strong radiographic changes.

Limitations and Error Sources in TAU

TAU measures pulsed ultrasound transmission through 32 different alveolar sites in the oral cavity. This is more sites than any other bone densitometer on the market, as far as the author is aware. The maxillary and mandibular bones have a unique combination of morphological structure and associated dental elements.

Potential sources of error when imaging the maxillary and mandibular alveolar bones in vivo with TAU are related to:
- anatomical configuration of the specimen;
- transducer and sensor array positioning;

Table 2
Grading Categories for Individual 3D Cube
Images (64 colums in each) of T Scans

τ Scan Grade	Description*
0	Cube shows no loss of column height and is 100% green; or mild loss of column height in less than 1/4 of columns; and/or moderate to severe loss of column height in less than 3 nonadjacent columns
1	Cube shows mild loss of column height in more than 1/4 of columns; and/or moderate loss of column height in less than 1/4 of the columns; and/or severe loss of height in less than 1/8 of the columns
2	Cube shows moderate loss of column height in 1/4 to 1/2 of columns; and/or severe loss of height in less than 1/4 of columns
3	Cube shows moderate loss of column height in more than 1/2 of columns; and/or severe loss of column height in 1/4 to 1/2 of columns
4	Cube shows severe loss of column height in more than 1/2 of columns

*Definition of loss of column height: mild (crown is green, less than 1/3 loss of height); moderate (crown is yellow or brown, 1/3 to 2/3 loss of height); severe (crown is orange or red, more than 2/3 loss of height).
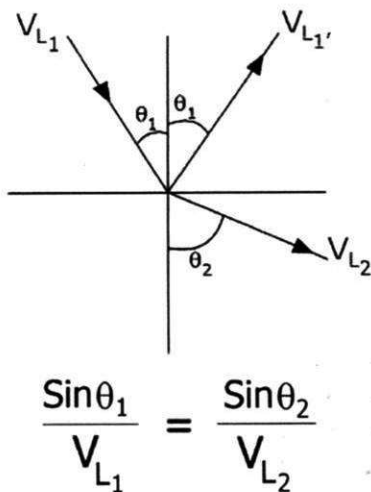
- bone properties and tissue thickness;
- acoustic transmission between the various media;
- patient cooperation.

Limitations related to anatomical configuration can interfere with the proper positioning of the sensor array against the lingual or palatal aspect of the alveolar ridge.

Errors induced by variations in the positioning of the transducer and sensor array are related to geometric optics which will impact on the accuracy of the imaging since, unlike x-rays that always travel in a straight line, acoustic radiation is sensitive to the angle of entry as described by Snell's law which describes the relationship between the angles and the velocities of the waves. Snell's law equates the ratio of material velocities VL1, and VL2 to the ratio of the angle of incident (sin_1) and refraction (sin_2) angle, as shown in the equation and graphic representation (**Figure 9**).

The formula (**Figure 9**) is valid for longitudinal waves which exist both in liquids and solids. Since cancellous bone is a heterogenous, anisotropic, dual phase medium, shear waves are also formed. This is called mode conversion (**Figure 10**).

Errors induced by bone properties include the variability of bone thickness, bone marrow composition and the ratio of cortical to trabecular bone. Since attenuation and TOF are dependent on distance travelled by the acoustic wave, measurements based on a standardized thickness instead of actual thickness are less than optimal. As long as the goal is to identify a change in bone density and/or quality, small variations in thickness are not as significant and this has been confirmed by a recent study involving the author and showing a high degree of correlation

between high grade TAU Scans and intramedullary pathological changes.[55] However, when the goal is the precise spatial localization of a defect in the specimen, accurate measurement of the thickness of the specimen as well as the thickness of soft tissue relative to the thickness of the alveolar ridge is necessary.
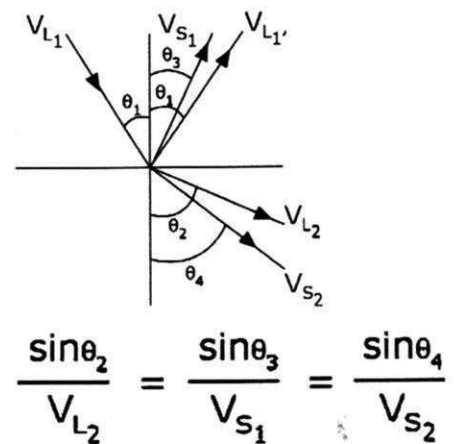
Another potential source of error with the Cavitat Ultrasonograph is the lack of a built in mechanism to regularly check calibration of the device. Manufacturers of QUS devices provide a phantom to allow the operator to verify the calibration of their devices on a daily basis. This can be done manually or through software integrated with the device. The Cavitat Ultrasonograph is calibrated by the manufacturer but a phantom or other suitable mechanism is not provided to allow the operator to routinely verify if the device is still properly calibrated.

For these reasons and others that may yet to be identified, the author recommends that the three golden rules of ultrasound imaging be followed[48]:

1. Use more than one image to make an interpretation;
2. Just because a feature is displayed do not consider that it is necessarily real;
3. Just because a feature is not displayed do not consider that it is necessarily not there.

Effectiveness of TAU

Early investigations with porcine mandibles have determined the safety of the generated sound waves and also determined the optimal frequency for complete transmission through alveolar bone as well as the detection of intra-medullary defects[49] (**Figure 11**).

$$\frac{Sin\theta_1}{V_{L_1}} = \frac{Sin\theta_2}{V_{L_2}}$$

Figure 9
Refraction of an acoustic wave between two mediums of the same type but with different acoustic impedance.

$$\frac{sin\theta_1}{V_{L_1}} = \frac{sin\theta_2}{V_{L_2}} = \frac{sin\theta_3}{V_{S_1}} = \frac{sin\theta_4}{V_{S_2}}$$

Figure 10
In solids shear waves are produced and are refracted at a different angle due to their lower velocity.
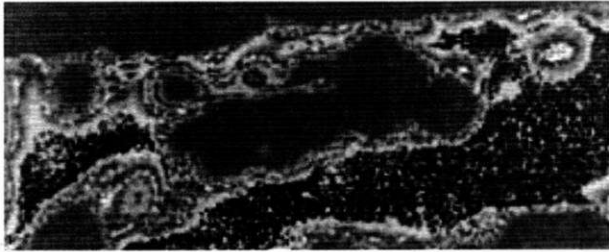
Figure 11
The first prototype version of the Cavitat was tested by the New Mexico Institute of Technology on porcine jaws for safety and effectiveness. Holes were drilled in the jaws and sound was then sent through the jaws in an attempt to see the holes. The sonogram shows several rounded holes (the drilled holes), but also shows several irregular hollow marrow spaces.

As an ultrasonic imaging device, the Cavitat Ultrasonograph was tested for acoustic output in accordance with Food and Drug Administration (USA) requirements for diagnostic ultrasound to confirm the safety of the device. The effectiveness of the device was demonstrated by two clinical studies in which both radiographs and ultrasound based, 3-dimensional images of alveolar sites were compared and confirmed with histopathology examination. The result of the studies confirmed that the device is effective as an adjunct to standard radiographic evaluation and clinical diagnostic procedures.[51,52]

The TAU device received regulatory approval from the FDA in February 2002 and from Health Canada in July 2002.[53]

Additional clinical studies have confirmed the effectiveness of the Cavitat Ultrasonograph for alveolar cancellous bone density and quality evaluation. One study compared radiographic images and τ scan images from 72 human subjects and 170 scanned alveolar sites which had been biopsied and given a microscopic diagnosis of osteoporotic or ischemic medullary disease. The images were graded according to a 4-point scale relative to severity of image alteration from normal. Of the 72 patients, 68% were women, and 82% were 40-69 years of age at diagnosis. Of the 170 imaged sites, both jaws were evenly distributed and 57% of the lesions were located in the retromolar/third molar region; 83% were in edentulous areas. Thirty-five (35%) of the radiographs were completely "normal " (false negative tests), while only one lesion was completely "normal" on τ scans. The average grade for radiographs of osteoporotic regions was 1.1 (median: 1; 95% CL: 0.92-1.22) compared to an average grade of 3.4 (median: 4; 95% Cl: 3.18-3.43) for τ scans. The average grade for radiographs of ischemically damaged bone was 0.8 (median: 1; 95% CL: 0.65-1.01), compared to 3.5 (median: 4; 95% CL: 3.39-3.61) for τ

scans. Eighty-six percent (86%) of positive scans were high-grade, i.e., grade III & IV lesions while only 9% of positive radiographs were high-grade. Therefore, it was concluded that τ scan typically showed great image alteration for ischemic and osteoporotic bone and that TAU imagery appeared to be significantly superior to routine dental radiology for detection of osteoporotic and ischemically diseased alveolar cancellous bone.[54]

Another study[55] was conducted to correlate τ scans with medullary histopathology in a large number of cases and to determine the proportion of false positive results. The study was based on a total of 3,522 scanned alveolar sites with 339 sites, in 125 patients, biopsied after τ scanning. Diagnoses were categorized into five broad disease types, which were then correlated with graded (4-point grade scale, see section entitled TAU Grading) τ images of the biopsied sites. Average patient age was 52 years, with 65% being female. Seventy-seven percent (77%) of lesions were in the molar/retromolar region. There was a slight predilection for the maxilla. Osteoporotic and ischemically damaged bone accounted for 61% of all microscopic diagnoses and 74% of suspicious sites had high-grade τ images, i.e., were Grade III or IV. The mean grade for these two disease types was 3.5 (median: 4) compared to 1.8 for normal bone; 95% Cls did not overlap. The level of false positive τ scans was approximately 2%, so the conclusion was that t imaging appears to be an excellent adjunctive tool for identifying ischemically damaged and osteoporotic alveolar bone. However, the t-test is technique-sensitive, and mistakes in technique can give false positive results, so the authors recommended that only images rated as Grade III or IV be considered for surgical exploration.

It should be noted that in the above-mentioned study, TAU demonstrated a relatively poor ability to detect periapical and odontogenic inflammatory lesions. Odontogenic cyst and fibroma, while well demarcated on radiographs, scanned as grade 0 or 1, i.e., negative τ scans. This is likely due to the fact that sound travels so well within the peripheral bony wall surrounding most periapical pathoses, developmental odontogenic cysts and benign odontogenic neoplasms. Conversely poorly radiographically demarcated lesions lacking a high-conduction peripheral wall, such as a myxoma, scanned as a high Grade III lesion.

Clinical Significance of TAU for Oral Bone Densitometry

The National Institute of Health (NIH) considers osteoporosis as a devastating disorder with significant physiological, psychological, and financial consequences.

While its impact on craniofacial bones is acknowledged, there is a lack of reliable prevalence rate and the NIH recommends that more attention should be paid to the skeletal health, especially in persons with conditions known to be associated with secondary osteoporosis.[56]

Recent investigators have demonstrated a significant association between BMD of the mandible and the peripheral skeleton in postmenopausal women. Some studies also have linked low BMD of the mandible and the peripheral skeleton with alveolar bone loss of the mandible and tooth loss.

In a review of the literature in 1997, Hildebolt[57] concluded that an association between osteoporosis and oral bone loss existed while recommending additional longitudinal studies. He suggested that inexpensive methods must be developed for sensitive and specific measures of oral bone loss.

More recent studies[58,59] have cited osteoporosis as a risk factor for periodontal disease even while their association is still not well understood. There is evidence that patients with systemic osteoporosis are likely to have decreased oral bone density, which may affect treatment decisions. Further, patients with decreased bone mineral density, indicative of osteoporosis, may be at a higher risk for periodontitis. Therefore, osteoporosis, could be considered a risk factor for periodontitis.[60]

In another study[61] based on 11,655 subjects in the US (5733 males and 5922 females), possible association of periodontal disease with femoral BMD were investigated. Women with high calculus scores and low BMD had significantly more clinical tooth attachment loss than those with normal BMD and similar calculus scores, These finding suggest that in presence of high calculus score, females with osteoporosis were at increased risk for tooth attachment loss. Other studies[62,63] have concluded that available evidence supported the role of systemic bone loss in the development of tooth loss among postmenopausal women. However, because so many possible factors contribute to the development of osteoporosis and periodontal diseases, it is difficult to establish a direct correlation between tooth loss, bone loss and loss of attachment resulting from periodontitis and decreased BMD associated with osteoporosis, though studies are ongoing.[50]

In general, the interpretation of the existing literature is difficult due to the different methods used to measure osteoporosis and oral bone loss. Most of the studies so far are confined to postmenopausal women, and several other acquired, behavioral, local and systemic factors contributing to bone loss such as genetics, hormone intake, gender, age, race, smoking, diet, oral hygiene, occlusal trauma, psychological stress, socio-economic, as well as immunological factors need to be addressed when assessing the relationship between osteoporosis and periodontitis.

Numerous studies have established an association between periodontal diseases and various systemic diseases including cardiovascular diseases. For example, DeStefano, et al.[64] focused on the contribution of periodontitis and analyzed coronary heart disease and mortality outcomes in nearly 10,000 subjects followed for 14 years longitudinally in the NHANES I study. Periodontitis for this cohort study was assessed with the periodontal index. Overall, subjects with periodontitis had a 25% increased risk for coronary heart disease relative to those with minimal periodontal disease. This association occurred after adjustments for potential confounders like age, gender, race, education, marital status, systolic blood pressure, total cholesterol levels, body mass index, diabetes, physical activity, alcohol consumption, poverty and cigarette smoking. For males younger than 50 years, periodontitis more strongly affected the incidence of coronary heart disease with a relative risk of 1.72.

Lately, data regarding the periodontal microbial challenge support the biological plausibility of the associations seen in human population studies. Hertzberg, et al.,[65,66] have reported that two oral microbes, streptococcus sanguis and p. gingivalis, express a collagen-like platelet aggregation-associated protein that can stimulate thrombotic events.Genco, et al.[67] presented preliminary data that suggest an odds ratio of 2.8 for subjects harboring p. gingivalis in periodontal pockets and exhibiting a myocardial infarction. In addition, Zambon, et al.,[68] recently isolated DNA sequences specific for periodontal pathogens like P. gingivalis and A. actinomycetemcomitans from human atheroma specimens using polymerase chain reaction (PCR) techniques. Other nonperiodontal infectious agents like clamydia pneumoniae, heliobacter pylori, herpes simplex, and cytolomegalovirus have been previously detected in atheromatous lesions using similar methods, and further support an infectious etiology for cardiovascular disease.[69]

There is also mounting evidence supporting the association of cardiovascular diseases and osteoporosis. Calcification is a common feature of atherosclerotic plaques, and osteoporosis is associated with both atherosclerosis and vascular calcification.[70,71]

The association of periodontal diseases with oral/systemic osteoporosis and cardiovascular diseases, in light of the association of cardiovascular diseases with osteoporosis, is interesting since other medullary oral bone pathologies associated with LBD such as regional ischemic osteoporosis (RIO), bone marrow edema (BME) and ischemic osteonecrosis (IO) with its many hollow,

air-filled spaces and its dry bone and fibrous marrow, have been identified[72,73] and linked with hypercoagulability,[74-78] a known risk factor in cardiovascular diseases. IO has also been associated with chronic facial pain.[79-82] The role of hypercoagulability in osteoporosis and periodontal diseases is thus an issue that warrants further research.

The available evidence supports early detection of oral osteoporosis as a sound clinical practice in the prevention and treatment of oral and systemic diseases associated with oral and systemic osteoporosis.

TAU has been demonstrated to be effective in imaging LBD in cancellous alveolar bone, and low bone density (LBD) is a characteristic of osteoporosis and related bone pathologies. The efficacy of the use of ultrasound in this application is also supported by previously published data showing a significant linear correlation between ultrasound velocity and cancellous bone density.[26]

TAU can provide valuable additional information on alveolar bone density which, used in combination with radiography, can assist the clinician in the diagnosis and treatment of cancellous bone pathologies associated with LDB (**Figure 12**).

Conclusions

TAU imaging is a safe, effective medical modality and a valuable clinical tool that can help clinicians in the early detection, diagnosis and treatment of the various forms of oral osteoporosis and associated oral pathologies.

Information derived from a τ scan is not meant to be used purely on it's own, but as part of a comprehensive clinical assessment using other established imaging modalities and diagnostic procedures. It is then that information on bone density and quality derived from TAU is most useful and can be used in various fields of dental medicine, including periodontology, maxillofacial surgery, maxillofacial pathology, implantology, endodontics and general dentistry.

The Cavitat Ultrasonograph has a small footprint that can be installed in almost any dental surgery to complement existing radiographic equipment and to provide additional diagnostic information on oral bone density and quality. It could also facilitate clinical research into oral etiological factors involved in various form of oral osteoporosis which, in combination with known systemic factors, could be aggravating factors in the disease processes.

Acknowledgements

TAU Scan - Quadrant #4 - Posterior region   Surgical view of exposed lesion
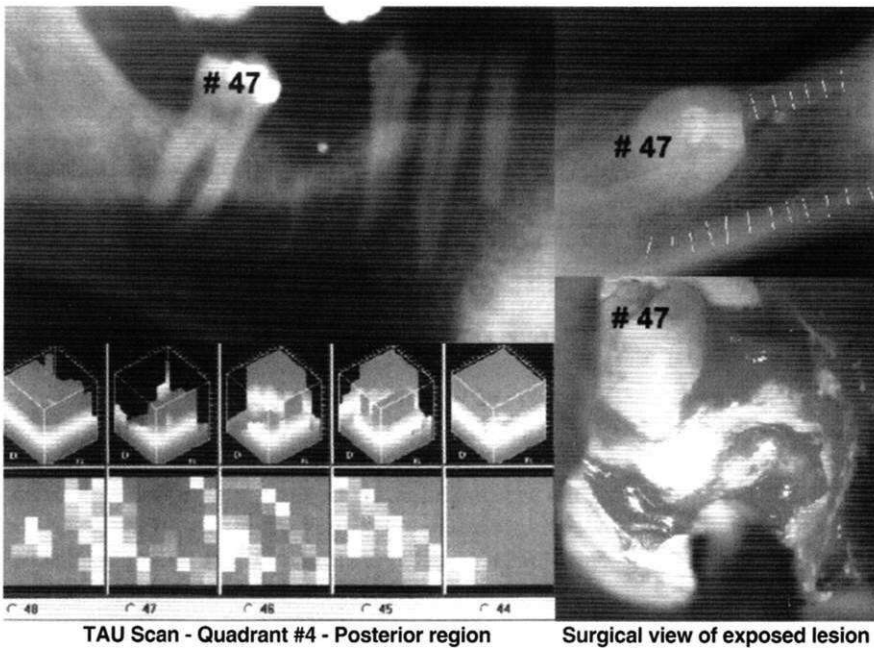
Figure 12
Lower right quadrant: a comparison of roentgenographic imaging, TAU imaging, and the actual lesion in the cancellous bone. The margins of the lesion have been highlighted on the occlusal film which shows the lesion more clearly than the orthopantomographic view, because the internal aspect of the occlusal cortical plate was damaged. The histopathological diagnosis in this particular case was regional ischemic osteoporosis (RIO). Tooth #47 (US #31) was vital and retained. This is a good example of the diagnostic benefits derived from the combination of roentgenographic and ultrasonographic imaging.

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