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(54) **Equipment and method for calibration and quality assurance of an ultrasonic bone analysis apparatus**

(57) A method of calibrating an ultrasound bone analysis apparatus having a pair of transducer assemblies. Each transducer assembly has a transducer and a coupling pad, and is movable relative to the other so that a face of each pad can be moved to a position in which they mutually contact at a first compression and to a position where the faces contact body parts at a second compression different than the first compression. The method according to the present application includes transmitting an ultrasound signal from one transducer and receiving a signal corresponding to the transmitted ultrasound signal through the other transducer when the transducer assemblies are in the first position and the second position. A time for the ultrasound signal to pass through the body part is determined, and a width of the body part based on positions of the transducers is determined. Then, using the time and width values a speed of sound of the ultrasound signal passing through the body part with squish compensation is calculated.

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Description

CROSS REFERENCE TO RELATED APPLICATIONS

5 [0001] The present application is a continuation-in-part of application Serial No. 08/866,804 filed on May 30, 1997, which is a continuation-in-part of application S.N. 08/477,580 filed on June 7, 1995, both of which are hereby incorporated herein by reference in their entirety.

BACKGROUND

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1. Field of the Invention

[0002] This invention relates to the field of ultrasonic analysis of bone tissue in humans, and more particularly to a bone analysis apparatus as well as an improvement in the calibration and quality assurance of an ultrasonic bone analysis apparatus by using, for example, phantoms.

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2. Description of the Related Art

[0003] The use of ultrasound in methods for detecting changes in bone characteristics is known. In particular, an ultrasound bone analysis apparatus has been used to analyze the properties of the heel bone or *os calcis*. The use of ultrasound is advantageous because it is non-invasive and is well-suited to repeated measurements or studies during medication since no ionizing radiation is used.

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[0004] Precision and reliability of the ultrasonic bone analysis apparatus, as with other medical diagnostic instrumentation, are a matter of substantial importance. Therefore, the apparatus undergoes calibration and quality assurance regularly during its lifetime. Rather than using a human subject, the calibration and quality assurance is performed using a substitute medium that has specific ultrasonic properties. The calibration and quality assurance facilitate adjustment of the apparatus according to the specification of the instrument.

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[0005] An ultrasonic bone analysis apparatus typically measures the rate of change of attenuation of ultrasound with frequency in the range of 200 to 600 kHz ("broadband ultrasound attenuation" or "BUA"), and also the speed of passage of acoustic waves ("speed of sound" or "SOS") through the bone. The BUA is a relative quantity calculated using a baseline signal as a reference of the transmitted signal entering the bone.

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[0006] The baseline is typically acquired by measuring the signal after passage through a reference medium. Because the reference signal is used to assess the transmitted signal, the reference medium should either minimally affect the ultrasonic signal or be well characterizable by, for example, having a known attenuation vs. frequency function.

35

[0007] Some existing ultrasonic bone analysis systems use a liquid as a coupling medium between the ultrasound transducers and the patient's foot. These "wet systems" require immersing the patient's foot in a liquid bath in order to achieve acoustic coupling. These wet systems typically use, for example, water or water/saline solutions as the coupling medium.

[0008] However, since the SOS of water is temperature dependent, existing wet systems require the use of water heaters for heating the water to a predefined temperature at which the SOS is known. Accordingly, these systems are relatively costly to produce and operate. In addition, when a patient's heel is placed in the water, the temperature of the water may vary, which can also vary the accuracy of the measurements.

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[0009] For calibration and quality assurance of an ultrasonic bone analysis apparatus, phantoms are sometimes used. While some commercially available phantoms are suitable for monitoring temporal changes in scanner performance, the acoustic properties of these phantoms are typically significantly different from those of bones such as the *os calcis*. Therefore, these phantoms might not adequately mimic the human foot.

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[0010] Heretofore, Clarke et al. proposed in "A Phantom for Quantitative Ultrasound of Trabecular Bone", 39 Phys. Med. Biol. 1677-87, to use a phantom as a substitute medium in a wet system. The proposed phantom consists of a rectangular block manufactured from a mixture of liquid epoxy and gelatine particles. While the proposed phantom does have acoustic properties similar to bone and may be adequate for experimental purposes, Clarke et al. admit that the proposed phantom has a number of unsolved practical problems such as durability.

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[0011] A phantom manufactured from an epoxy and glass bead mixture has also been used with a wet system. However, the manufacture of this phantom is believed to be complex and to require substantial supervision and control.

[0012] The measurement of SOS depends on the ambient conditions. Measuring accurately and comparing SOS data can be difficult due to the wide range of possible conditions, and such difficulties can be aggravated by imprecise control and determination of the conditions of the measurement.

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[0013] Various media have been used for testing SOS measurements as well as for use as the acoustic coupling medium in the wet system as noted above. For example, pure water and saline solution of various sodium chloride con-

centrations have been employed. However, the SOS for each of these substances varies according to temperature, each substance having a positive temperature coefficient. Therefore, using one of these substances in the testing of the SOS measurements or when measuring the actual SOS through a patient's heel, has the disadvantage that temperature is an additional variable.

5

SUMMARY

[0014] A method of calibrating an ultrasound bone analysis apparatus having a plurality of transducer assemblies with a respective plurality of transducers and a respective plurality of coupling pads and measuring a SOS of a body part. The method comprises providing a plurality of coupling pads having a SOS substantially similar to the SOS of the body part to be analyzed. The plurality of transducer assemblies are adjusted until the plurality of coupling pads are mutually in contact, the plurality of coupling pads mutually contacting each other using a first amount of pressure. An ultrasound signal is transmitted through one of the plurality of transducers. A signal corresponding to the transmitted signal is received through another one of the plurality of transducers. A first propagation time of the transmitted signal and a first position of the transmitting and receiving transducers are determined. A body part is positioned between the plurality of coupling pads, the coupling pads contacting the body part using a second amount of pressure different than the first amount of pressure and an ultrasound signal is transmitted through the transmitting transducer. A signal corresponding to the transmitted signal is received through the receiving transducer and a second propagation time of the transmitted signal and a second position of the transmitting and receiving transducers are determined. A time for the ultrasound signal to pass from the transmitting transducer to the receiving transducer is determined based on the first and second propagation times and a width of the body part is determined based on the first and second positions. The step of positioning a body part between the plurality of coupling pads can include applying a non-aqueous gel between the body part to be analyzed and the coupling pads.

[0015] A method for calibrating an ultrasound bone analysis apparatus comprises providing a phantom having a frequency attenuation approximating a body part to be analyzed and having a predetermined speed of sound (SOS) and broadband ultrasound attenuation (BUA) measured at a predefined temperature. Calibration of the ultrasound bone analysis apparatus is performed at an arbitrary temperature, the calibration comprising, adjusting the plurality of transducer assemblies so that the plurality of coupling pads are mutually in contact, transmitting an ultrasound signal through one of the plurality of transducers, receiving a signal corresponding to the transmitted signal through another one of the plurality of transducers and determining a first propagation time of the transmitted signal and a first position of the transmitting and receiving transducers. The phantom is positioned between the plurality of coupling pads so that the coupling pads contact the phantom, an ultrasound signal is transmitted through the transmitting transducer, a signal corresponding to the transmitted signal is received through the receiving transducer and a second propagation time of the transmitted signal and a second position of the transmitting and receiving transducers are determined. A SOS of the ultrasound signal passing from the transmitting transducer to the receiving transducer based on the first and second propagation times and a width of the phantom based on the first and second positions are determined. The determined SOS is compared to the predetermined SOS of the phantom and based on the result of the comparison, an amount of change in BUA of the phantom is determined. A BUA reference curve and an additive constant are stored in memory based on the result of the comparison. The step of positioning the phantom between the plurality of coupling pads includes applying a non-aqueous gel between the phantom and the coupling pads. The additive constant may include a correction term derived from the result of the comparison performed in the comparison step. The additive constant includes the predetermined BUA measured at the predefined temperature.

[0016] A method is disclosed for performing a quality control evaluation on an ultrasound bone analysis apparatus. The method comprises determining a direction of change in BUA of a phantom by measuring a signal through the phantom and calculating BUA of the phantom and comparing to a previously determined BUA value for the phantom. A direction of change in SOS of the phantom is determined by measuring a signal through the phantom and calculating based thereon SOS through the phantom and comparing to a previously determined value for the phantom. An evaluation of the condition of the apparatus is performed based on the results of the determinations of the directions of change of the BUA and SOS. The evaluating step may comprise determining if the directions of change in SOS and BUA are in the same directions, wherein if the directions of change in SOS and BUA are not in the same directions, a malfunction of the apparatus is indicated to an operator.

[0017] A method is disclosed for evaluating parts of an ultrasonic bone analysis apparatus, comprising, performing quality control evaluations or calibration measurements on the apparatus utilizing a phantom, wherein during the evaluations or measurements, a width of the phantom is measured. The measured width of the phantom is at least periodically stored. A measured width of the phantom is compared to a stored width of the phantom, determining, based on the comparison, a variation in squish of the transducer pads. An evaluation of a condition of the transducer pads is made based on the determination.

[0018] A transducer assembly is disclosed for use in an ultrasound bone analysis apparatus, the transducer assem-

bly comprising, a plurality of transducers, a plurality of coupling pads each of which covers at least a portion of a corresponding one of the plurality of transducers, and an acoustic coupling material provided between the transducer and the respective coupling pad, the acoustic coupling material comprising a material having a temperature independent speed of sound. The acoustic coupling material has a substantially zero temperature coefficient of sound propagation over a large range of temperatures. The acoustic coupling material may comprise a water and ethyl alcohol mixture, the mixture being 17% alcohol by weight.

[0019] An ultrasound bone analysis apparatus is disclosed comprising a pair of transducer assemblies, each comprising a transducer, a coupling pad which covers at least a portion of the transducer and an acoustic coupling material provided between the transducer and the respective coupling pad, the acoustic coupling material comprising a material having a temperature independent speed of sound, a time measuring device for measuring a propagation time of ultrasound based on a signal transmitted between said transducers, a distance measuring device for measuring at least one of a distance between the transducers and a width of a body part to be analyzed, and a processor for determining a speed of sound of a body part to be analyzed based on the measurements performed by said time measuring device and said distance measuring device. The apparatus may further comprise a unit for moving the transducer assemblies between various positions, including a position in which the coupling pads contact each other and a position in which the coupling pads contact a body part to be analyzed. The acoustic coupling material may have an SOS substantially similar to that of a body part to be analyzed. The apparatus may further comprise biasing units for biasing the pair of transducer assemblies such that the biasing units bias the coupling pads against each other at a first pressure and bias the coupling pads against the body part to be analyzed at a second pressure different than the first pressure.

[0020] An ultrasound bone analysis apparatus is disclosed comprising a container for containing an acoustic coupling material and capable of containing at least a portion of a body part to be analyzed within the acoustic coupling material, the acoustic coupling material comprising a material having a temperature independent speed of sound. The apparatus comprises a pair of transducer assemblies, each comprising a transducer and a coupling pad which covers at least a portion of the transducer. Each of the transducer assemblies is arranged on opposite sides of the container for transmitting and receiving ultrasound. A time measuring device measures a propagation time of ultrasound based on a signal transmitted between the transducers, and a processor determines a speed of sound of a body part to be analyzed based on the measurements performed by the time measuring device. The acoustic coupling material may have a substantially zero temperature coefficient of sound propagation over a large range of temperatures. The acoustic coupling material may comprise a water and ethyl alcohol mixture, the mixture being 17% alcohol by weight.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Preferred embodiments of the invention are described hereinbelow with reference to the drawings wherein:

- Fig. 1 is a perspective view of a foot well assembly of an ultrasonic bone analysis apparatus that can use phantoms according to the present application;
- Fig. 2 is a sectional view of a transducer drive mechanism of the ultrasonic bone analysis apparatus;
- Figs. 3A and 3B are front and side views of a position encoder of the ultrasonic bone analysis apparatus;
- Fig. 4 is a block diagram showing control of the transducer drive mechanism of the ultrasonic bone analysis apparatus;
- Figs. 5A and 5B are front and side views of a pad/delay unit of the ultrasonic bone analysis apparatus;
- Fig. 5C is a contour diagram of an end of the pad/delay unit;
- Fig. 6A is a front view of a first phantom according to the present invention;
- Fig. 6B is a sectional view of the first phantom taken essentially on the line 6B--6B of Fig. 6A;
- Fig. 7A is a front view of a second phantom according to the present invention;
- Fig. 7B is a sectional view of the second phantom taken essentially on the line 7B--7B of Fig. 7A;
- Fig. 8A is a front view of a third phantom according to the present invention;
- Fig. 8B is a sectional view of the third phantom taken essentially on the line 8B--8B of Fig. 9A;
- Figs. 9A and 9B are a perspective view and an exploded view, respectively, of a transducer assembly of the ultrasonic bone analysis apparatus;
- Fig. 10 is a block diagram showing control of temperature of a phantom of the present invention;
- Fig. 11 is a sectional view of an embodiment of a transducer drive mechanism of the ultrasonic bone analysis apparatus;
- Fig. 12, is a sectional view of an embodiment of a transducer drive mechanism of the ultrasonic bone analysis apparatus;
- Fig. 13 is a perspective view of a foot well assembly of an ultrasonic bone analysis apparatus that can use phantoms according to the present application; and
- Fig. 14 is a sectional view of an embodiment of a transducer assembly of the ultrasonic bone analysis apparatus.

DETAILED DESCRIPTION**Ultrasonic Bone Analysis Apparatus**

5 **[0022]** Referring to Fig. 1, an ultrasonic bone analysis apparatus with which the phantoms according to the present application can be used has a foot well assembly 3. The foot well assembly 3 includes a box cover 38 having a foot support 39, and foot well bottom 37. The foot support 39 has an area slightly larger than a human foot. Transducer ports 36 are located on the sides of the foot support 39, towards the rear. Bridge brackets 30 with respective channels 31 which are located along the sides of the foot support 39 facilitate the mounting of a shin guide assembly (not shown) for
10 restraining the foot and lower leg.

[0023] Referring now to Fig. 2, a transducer drive mechanism of the ultrasonic bone analysis apparatus includes a pair of transducer assemblies 110. The transducer assemblies 110 include respective transducers 101, respective acoustical delay lines 109 and respective coupling pads 102.

[0024] The transducer assemblies 110 are mounted to respective carriages 103 that slide along a lateral-medial
15 axis. The carriages 103 are provided with sufficient freedom of movement such that the respective coupling pads 102 can be brought into mutual contact. Respective compression springs 104 attached to the carriages 103 apply opposing lateral forces towards the center of the foot or phantom. The carriage/spring assembly is free floating and will center itself on the foot or phantom with equal pressure on both sides.

[0025] An extension spring 105 applies the initial pressure when the coupling pads 102 reach the phantom or the
20 patient's foot. To adjust the pressure in small increments, a stepper motor with rack and pinion mechanism 106 will move a finite number of steps and compress the compression springs 104 that are attached to the respective carriages 103. The compression springs 104 will pull the respective transducers 101 and pads 102 inward at a force proportional to the spring rate and distance translated.

[0026] The distance between the transducers 101 is continuously measured by means of a position encoder 120
25 that is mechanically linked to the motion of the transducers 101. Figs. 3A and 3B illustrate respective front and side views of the position encoder 120. The position encoder has a code strip 121 mounted onto one of the carriages 103 and an optical encoder reader 122 mounted on the other of the carriages 103. As the distance between the transducers 101 changes, the code strip 121 moves between the slot of the optical encoder reader 122, and the optical reader 122 reads lines 123 of the code strip 121 as the lines 123 are traversed.

[0027] Referring to Fig. 4, the stepper motor with rack and pinion mechanism 106 under the control of controller 200
30 automatically positions transducers 101 against the patient's heel or the phantom with sufficient pressure to insure ultrasonic coupling. Signals received by the receiving transducer 101 are supplied to the controller 200. The microprocessor-based controller 200 controls the execution of system and application software and has a timer 203 and input/output circuitry 205 for interfacing with user input 220 and display device 210. Data and the system and application
35 software are stored in memory 201 (e.g., RAM and ROM).

[0028] Preferably, the controller 200 controls the operations of the stepper motor 106 according to positional data supplied by the position encoder 120. The controller 200 monitors the position encoder 120 throughout the measurement to detect movement of the transducers 101 which may have a deleterious effect on the measurement.

[0029] Alternatively, the controller 200 determines the quality of the signals received by the receiving transducer
40 101 at least in part according to the attenuation of the signals, and controls the operations of the stepper motor 106 according to the quality of the signals received by the receiving transducer 101 and positional data supplied by the position encoder 120. These steps are repeated by the controller 200 until the signals received by the receiving transducer 101 achieve a predetermined quality.

[0030] The controller 200 determines other parameters of interest, including BUA and bone velocity. Also, the controller 200 uses timing data supplied by the timer 203 to determine the arrival time of the received ultrasonic signal combined with timing data for the reference signal which is stored in memory and the distance between the transducers as determined by the position encoder 120 to calculate the speed of the ultrasonic signals through the foot or phantom (or the SOS).

[0031] The controller 200 uses temperature readings from temperature sensor 250 to improve the accuracy of the
50 position encoder measurements and correct for temperature dependent inaccuracy in the ultrasound measurement. For example, the controller 200 accounts for linear expansion of the encoder strip 121 by applying a temperature dependent term to the data supplied by the position encoder 120. Additionally, the controller 200 applies a temperature dependent term to correct an estimation of the time delay through the delay line 109 and the coupling pad 102. The controller 200 also applies a temperature dependent term to correct an estimation of the frequency-dependent attenuation
55 of the coupling pad 102. Furthermore, the controller 200 uses the temperature reading to determine if the apparatus is operating within the specified environmental range allowed, and if not, the operator is informed that the apparatus is not ready to be used.

[0032] The coupling pads 102 have a durometer corresponding to a sufficiently flexible waveguide that can partially

conform to the shape of a foot. The shape of the pads 102 conforms to the heel to eliminate any gaps between the foot and pad. The surfaces of the pads 102 which contact the transducers 101, the delay line 109, or the patient's skin is shaped at an angle to the propagation axis to reduce the acoustic reflection at the pad-to-skin interface by spreading the reflected energy over time and position.

5 [0033] The coupling pad 102 and the delay line 109 are integrated into a single pad/delay unit 150 to reduce an extraneous reflection between a pad-to-delay-line interface. Figs. 5A and 5B illustrate top and side views of the pad/delay unit 150. The surface of the pad that contacts the patient's skin is shaped to expel air bubbles from the contact area when pressure is applied. Fig. 5C shows the contours of the surface of the pad/delay unit 150 which contacts the patient's skin.

10

A First Phantom

[0034] When executing software for calibration or quality assurance, the controller 200 via the display device 210 prompts the operator to insert a phantom in the foot support 39 of the foot well assembly 3.

15 [0035] Figs. 6A and 6B illustrate a phantom 260 having a cylindrical plug 262 cast inside a hard plastic housing 264. The cylindrical plug 262 is a soft elastic material having a very low attenuation coefficient. The sound impedance of the soft elastic material is relatively close to that of soft human tissue. The attenuation-versus-frequency profile of the material in the frequency range of 200-1000 kHz is substantially flat. The soft elastic material has a minimal effect on the ultrasonic wave, and a predetermined SOS.

20 [0036] The soft material is preferably an elastomeric, white castable polyurethane set to a durometer of 10 to 50 Shore A. One such material is Ciba-Geigy TDT 178-34, which has a durometer of 15 Shore A and is also the preferred material of the transducer pads 150.

[0037] Indentations 266 are provided on opposite sides of the cylindrical plug 262 to accommodate the respective transducer pads 150. The shapes of the indentations 266 complement the shapes of the respective transducer pads 150. The hard plastic housing 264 positions the cylindrical plug 262 properly in relation to the transducer pads 150 of the apparatus. The complementary shapes of the pads 150 and respective indentations 266 of the cylindrical plug 262 facilitate the coupling of the pads 150 with the plug 262.

25 [0038] The phantom 260 has approximately the width of the typical female heel, and thereby mimics the conditions at which the heel is measured. As a result, the reference signal spreads out in a pattern similar to that in an ultrasonic measurement of the heel.

30 [0039] When the phantom 260 is inserted in the apparatus, a signal is transmitted through the phantom. The controller 200 controls movement of the transducer assemblies 110 using feedback from the encoder 120. The received signal which had passed through the phantom 260 is used to calibrate the apparatus. The controller 200 saves data of the received signal in the memory 201 and uses the saved data in subsequent calculations of BUA. The controller 200 determines the frequency spectrum of the received signal which is used in the BUA calculation. The received signal that passed through the phantom 260 is used as a baseline with which a signal that passes through the foot is compared. The BUA calculation will be explained in more detail hereinbelow.

35 [0040] The phantom 260 is also used for quality assurance of the apparatus. In this mode, the controller 200 calculates the drift of the apparatus by using the measurement of the current received signal that passed through the phantom 260 and recorded measurements of past received signals that had passed through the phantom 260 which are stored in memory 201. The drift is temperature-dependent. Therefore, because the human foot is typically at 98.6 degrees F and the phantom 260 is at room temperature (generally between 60-90 degrees F), the measured value is temperature-corrected according to the temperature reading from the temperature sensor 250.

45 A Second Phantom

[0041] Referring to Figs. 7A and 7B, a phantom 270 is provided to mimic the BUA of the human foot. The phantom 270 attenuates an ultrasonic wave in the frequency range of 200-1000 kHz by approximately the same amount as a human foot. The attenuation-versus-frequency profile of the phantom 270 is substantially linear in the frequency range of 200-600 kHz and is approximately 1 dB/MHz per mm. This profile is very similar to the attenuation-versus-frequency profile of the human foot.

50 [0042] The phantom 270 is a cut, castable, or otherwise manufactured block of material 272 having indentations 276 on opposite sides thereof to accommodate the respective transducer pads 150. The shapes of the indentations 276 complement the shapes of the respective transducer pads 150. The complementary shapes of the pads 150 and respective indentations 276 facilitate the coupling of the pads 150 with the block 272.

55 [0043] The phantom 270 also has approximately the width of the typical female heel, and thereby mimics the conditions at which the heel is measured. The block 272 is shaped to position the phantom 270 properly in relation to the transducer pads 150 when the phantom 270 is placed in the foot support 39 of the apparatus.

[0044] The block 272 is preferably a castable polyurethane. One such polyurethane is black and has approximately an 80 Shore A durometer. The polyurethane block is simple to manufacture and suitably mimics the human foot.

[0045] Software for calibration and quality assurance also measures a received signal that passed through the phantom 270. The steps for acquiring this measurement are similar to the steps for acquiring a measurement of the signal that passed through the phantom 260, as set forth hereinabove.

[0046] The received signals that passed through the phantom 270 are used for quality assurance of the apparatus for a BUA measurement. The BUA of a measured signal is calculated in the frequency domain. The measured signal and the reference signal in the time domain are transferred to respective frequency-domain counterparts $|B(f)|$ and $|R(f)|$ by performing a Fourier Transform or a Fourier Series calculation. The BUA is the slope of a line fit to a function $A(f)$ in a specific frequency range. The function $A(f)$ is defined as follows:

$$A(f) = 20 * \log_{10} (|B(f)| / |R(f)|). \quad (1)$$

A commonly used frequency range is 0.2 to 0.6 MHz.

[0047] As mentioned hereinabove, the reference signal may be obtained by measuring a signal that passed through the phantom 260. Magnitudes of respective frequency components of this reference signal are used as the reference $|R(f)|$.

[0048] The same reference signal may be used as the reference for calculating the BUA of a signal that passed through the phantom 270. In such a calculation, the magnitudes of the respective frequency components of the signal that passed through the phantom 270 are the $|B(f)|$ of the measured signal.

[0049] The measurement of the received signal that passed through the phantom 270 is used by the quality assurance software to determine instrument drift. Because the phantom 270 mimics the human foot, the determined drift would reflect the expected drift when a human foot is analyzed using the apparatus. Again, because drift is temperature-dependent, the calculation includes a temperature correction term.

[0050] The second phantom can be used for calibration and storing a BUA baseline, using the fact that the SOS and BUA are both temperature dependent.

[0051] After manufacture of the second phantom, the SOS and BUA of the phantom are measured at a predefined temperature, typically 72° Fahrenheit. The measured SOS and BUA values are included on the label of the phantom when shipped from the factory and can be expressed as BUA (P_2, T_s) and SOS (P_2, T_s), where $T_s = 72^\circ$ Fahrenheit. However, calibration (e.g., daily or periodic calibration) of the instrument is typically performed at an unknown arbitrary temperature T_c . Accordingly, a need exists to accurately and efficiently perform BUA calibration at an arbitrary temperature.

[0052] From the above function $A(f)$, BUA can be written:

$$BUA = Slope_{i=200-600kHz} [-20 \log_{10} (\frac{|M_i|}{|R_i|})] \quad (2)$$

[0053] Where R_i is the fast fourier transform (FFT) of a non-attenuated reference signal and M_i is the FFT of the measured signal through the patient's heel.

[0054] In order to perform calibration, several variables must be accounted for, including R_i and temperature which are typically unknown quantities. Even if the ambient temperature was measured and known, the actual temperature of the phantom itself may still be difficult to determine. That is, because of the phantom's excellent insulative properties, the temperature of the phantom may not be at equilibrium with the ambient temperature during the actual measurements.

[0055] To account for the above-noted variables, the above question (2) can be written:

$$BUA = Slope_{i=200-600kHz} [-20 \log_{10} (\frac{|M_i|}{|P2_i(T_c)|}) (\frac{|P2_i(T_c)|}{|R_i|})] \quad (3)$$

[0056] Where $P2_i(T_c)$ is the FFT of the signal through phantom 2 at unknown temperature T_c . Equation (3) can be rewritten:

$$BUA = Slope_{i=200-600kHz} [-20 \log_{10} (\frac{|M_i|}{|P2_i(T_c)|})] + Slope_{i=200-600kHz} [-20 \log_{10} (\frac{|P2_i(T_c)|}{|R_i|})] \quad (4)$$

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The second part of equation (4) is the BUA of the phantom 2 at the unknown temperature T_c . Equation (4) can thus be rewritten:

$$5 \quad BUA = Slope_{i=200-600kHz} [-20 \text{ Log}_{10} (\frac{|M_i|}{|P2_i(T_c)|})] + BUA(P2, T_c) \quad (5)$$

[0057] Where BUA ($P2, T_c$) is the BUA of phantom 2 at unknown temperature T_c .

[0058] As noted above, during manufacture of the phantom 2, BUA ($P2, T_c$) and SOS ($P2, T_c$) were measured. At the time of BUA calibration, SOS ($P2, T_c$) can be measured using one of the methods described herein for example, and used to determine the change in BUA. That is, as will be appreciated by those skilled in the relevant art, the relationship between the change in BUA and SOS as a function of temperature is known, and can be readily determined for the material used to manufacture the phantom.

[0059] The change in temperature between the present arbitrary temperature T_c and the predefined temperature T_s can be expressed:

$$\Delta T = T_c - T_s \quad (6)$$

[0060] The change in SOS of phantom 2 can be expressed:

$$20 \quad \Delta SOS_{p2} = SOS(P2, T_s) - SOS(P2, T_c) \quad (7)$$

[0061] The change in BUA of phantom 2 can be expressed:

$$25 \quad \Delta BUA_{p2} = BUA(P2, T_s) - BUA(P2, T_c) \quad (8)$$

[0062] Rewriting and substituting expression (8) into expression (5) yields:

$$30 \quad BUA = Slope_{i=200-600kHz} [-20 \text{ Log}_{10} (\frac{|M_i|}{|P2_i(T_c)|})] + BUA(P2, T_s) - \Delta BUA_{p2} \quad (9)$$

[0063] BUA ($P2, T_s$) is the value printed on the label of the phantom. ΔBUA_{p2} , as noted above, can be easily derived from the change in SOS (ΔSOS_{p2}) which is easily calculated by measuring the SOS through phantom 2 as described in the present specification. The first part of expression (9) represents a reference curve which can be stored along with the second and third parts of the expression which represent an additive constant. These values can be used for calibration of the instrument. Accordingly, easy and efficient BUA calibration of the apparatus can be performed according to this embodiment of the present invention.

[0064] The known relationship between change in SOS and change in BUA can also be used for a quick and easy quality assurance determination. That is, the relationship between the change in SOS and the change in BUA can be used to make a quick determination whether there is a problem with the apparatus. For example, it is known that for a positive change in SOS, there should be a positive change in BUA. Accordingly, if during calibration it is determined that measured SOS has increased and measured BUA has decreased (or vice versa), it can be determined that there is a problem with the apparatus and an indication can be provided to the operator.

A Third Phantom

[0065] Figs. 8A and 8B illustrate a phantom 280 that has a substantially zero temperature coefficient over a range of normal ambient temperatures.

[0066] The temperature-independent phantom 280 has a housing 282 containing a mixture of ethyl alcohol and water which is 17% ethyl alcohol by weight. The housing 282 has a filler port 283 through which the mixture is introduced. A cap 285 plugs the filler port 283 after the mixture fills a receptacle 284 formed by inner walls of the housing 282. The plugged receptacle 284 is air-tight to prevent a change in alcohol concentration by evaporation of the alcohol or absorption of water by the mixture. The housing 282 is made from preferably a polymer such as polyurethane which has a predetermined SOS.

[0067] Indentations 286 are provided on opposite sides of the housing 282 to accommodate the respective transducer pads 150. The bottoms of the respective indentations 286 are parallel to respective adjacent inner walls 288 of the housing. Therefore, the shapes of the indentations 286 do not complement the shape of the respective transducer

pads 150. Nevertheless, because the pads 150 are elastomers, when the phantom is placed in the foot support 39, the transducer assemblies 110 can be moved under the control of controller 200 to compress the respective transducer pads 150 against the bottoms of the respective indentations 286 until there is adequate coupling. The compression of the transducer pads 150 does not affect the SOS measurement.

5 [0068] The housing 282 between each of the indentations 286 and the mixture should be relatively thin compared to the distance between the inner walls 288. The other portions of the housing 282 can be relatively thicker than the distance between the indentations 286 and the respective adjacent inner walls 288.

[0069] The phantom 280 also has approximately the width of the typical female heel, and thereby mimics the conditions at which the heel is measured. The housing 282 is shaped to position the phantom 280 properly in relation to
10 the transducer pads 150 when the phantom 280 is placed in the foot support 39 of the apparatus.

[0070] Because the housing 282 encloses the fluid mixture, the phantom 280 is convenient to use. Furthermore, the phantom 280 having a polymer housing is easily manufactured.

[0071] The phantom 280 is used to calibrate the apparatus for the SOS calculation. Furthermore, the phantom 280 can be used for quality assurance to measure instrument drift. Because the phantom 280 has a predetermined SOS
15 that is temperature-independent, the drift can be determined by comparing the measured value with the predetermined value. The steps for acquiring a signal that passed through the phantom 280 are similar to the steps for acquiring a signal that passed through the phantom 260, as set forth hereinabove.

[0072] The phantom 280 as described is substantially temperature-independent over a range of normal ambient temperatures because a mixture of ethyl alcohol and water which is 17% ethyl alcohol by weight is used. The temper-
20 ature independence is preferred. Alternatively, the 17% mixture can be replaced by pure water or a mixture of water and ethyl alcohol which has a predetermined temperature coefficient. Measurements of an ultrasonic signal that passed through a phantom using pure water or the alternative mixture would need to be adjusted with an appropriate temperature-correction term which can be determined by one skilled in the art.

25 **Mutually Contacting Transducer Pads**

[0073] A reference signal can be obtained by another method using the ultrasonic bone analysis apparatus without a phantom. The controller 200 controls movement of the transducer assemblies 110 until the transducer pads 150 are
30 mutually in contact. A received signal that passed through the mutually touching transducer pads can be used for many of the same purposes, which are described hereinabove, for which the received signals that passed through the phantom 260 is used.

[0074] It is desirable to obtain calibration measurements that account for variations in ultrasonic and electronic properties according to respective variation in temperature and time. The measurement of the received signal that
35 passed through the mutually contacting coupling pads is obtained relatively close in time to a measurement of a signal passing through a heel or a phantom interposed between the pads. Because proximity in time is accompanied, presumably, by proximity in ambient temperatures for the respective measurements, no correction for time or temperature drift between the measurements is required. Therefore, the measured signal obtained while the pads 150 are mutually touching may be used to compare with the signal that passed through the heel to measure quantities that are
40 of interest to bone quality without contamination of the measurement by the ambient temperature at which the measurement was taken.

[0075] The received signal that passed through the mutually touching pads may be used as a reference for a BUA measurement. Additionally, a propagation time of the ultrasonic signal through the mutually touching pads is measured and may be used as a reference time for propagation through the pads. The reference time measurement may be compared to the measurement of the signal that passed through the heel to determine a time of propagation through the
45 heel. The calculated time of propagation through the heel along with information about the width of the heel are used to calculate a SOS of the heel.

[0076] The received signal that passed through the mutually touching pads may be compared to an ultrasonic signal measured at a known temperature, and the time of arrival of the two may be used to calculate an effective temperature of the pads. The effective temperature may be used to adjust temperature-dependent coefficients of the BUA for
50 the temporally-proximate measurements of the signals that pass through the heel or phantom.

[0077] The transmission of an ultrasonic signal through mutually contacting coupling pads may produce a reflected signal from a reflection by either the interface between the pads, a reflecting object placed in the pads, or a non-transmitting transducer face. A measurement of the reflected signal may be used to determine a time of propagation through
55 all or part of the transmitting media, including the transducer 101 and the transducer pads 150, and scaled for comparison to the temporally-proximate measurement of the signal passing through the heel or phantom.

[0078] Transmission of an ultrasonic signal through non-contacting coupling pads can also produce a reflected signal. A measurement of the reflected signal produced from a reflection by either the interface between the pad and air, a reflecting object placed in the pads, or an object interposed between the pads may be used for the same purposes

as the measurement of the reflected signal produced by transmitting through mutually contacting coupling pads.

SOS Measurements

5 **[0079]** Measurements of the speed at which ultrasound signals pass through bone (SOS) and broadband ultrasound attenuation (BUA) involve various considerations. An important consideration in obtaining accurate determinations of the SOS is pad squish (i.e., the distance a pad is compressed when pressure is applied to it). It will be appreciated that because springs 104, 105 are used to bias the transducer pads against each other or against the heel, the amount of pressure the springs exert on the pads (e.g., the amount of compression or squish), will vary depending
 10 on whether the pads are contacting each other or whether they are contacting the patients heel. That is, there will be different compressions when the pads are in contact and when a heel is interposed between the pads. As will be described below, these variations in pressure or amount of squish does not effect the accuracy of measurements according to embodiments of the present invention. As noted, the SOS of a body part (e.g., the heel) is a function of the width "w" of the body part and the time "t" it takes the ultrasound to pass through the heel. The SOS of a body part is
 15 represented by the following expression:

$$\text{SOS} = w/t \tag{10}$$

[0080] As an illustration with a typical heel being about 33 mm wide, if the coupling pads squish by 1mm, the SOS determination may differ from an SOS determination with squish compensation by about 1/33 which is a 3.3 % difference. A more desirable difference in SOS measurements is below 1 % and is preferably about 0.3%.

[0081] Pad squish is dependent on various factors including pad stiffness, ambient temperatures and the age of the pad. For example, when the pads are pressed against the heel, stiff or rigid pads will have less squish as compared to pads which are more pliable. Further, the ambient temperature and age of the pad may affect the pliability of the pads.
 25 As a result, the width w and time t determinations may vary from measurement to measurement.

[0082] The speed of sound value with squish compensation (SOS') is represented by the following expression:

$$\text{SOS}' = w'/t' \tag{11}$$

30 The width w' is not the same as the width w of the body part (e.g., patient's heel), because the width w' includes the amount of squish when the coupling pads are touching and when the pads are pressed against the heel. The relationship between w' and w can be expressed as follows:

$$w' = w(1+\delta) \tag{12}$$

35 where δ is the difference between the amount of squish when the pads touch and when the pads contact the body part divided by the width w of the body part. Generally $\delta < 1$. Further, the time t' is not the same as time t because the ultrasound signal may travel a greater or lesser distance depending upon the amount of pad squish between the two measurements. The relationship between t' and t can be expressed as follows:

$$t' = t(1+\epsilon), \text{ where } \epsilon = ((w)(\delta)/\text{SOS}_{\text{pads}})/t \tag{13}$$

In the expression for ϵ , the numerator is the difference in squish of the two measurements divided by the SOS of the coupling pad material. This accounts for the time it takes the ultrasound to travel through the pads because of the
 45 greater or lesser squish of the coupling pads that occurs in the two measurements. Generally, the numerator is significantly smaller than the denominator because the time t it takes the ultrasound signal to pass through the body part is significantly greater than the time it takes the ultrasound signal to pass through the difference in pad squish.

[0083] As noted above, in order to obtain more accurate SOS values the relationship between the actual SOS and approximated SOS' determinations should be as close as possible. The relationship between the SOS and SOS' can
 50 be derived as follows. Substituting the theoretical values for w' and t', SOS' can be expressed as:

$$\text{SOS}' = (w/t)(1+\delta)/(1+\epsilon) \tag{14}$$

Since ϵ is substantially smaller than one, the above equation can be expanded as a power series which results in the
 55 following expression with SOS substituted for w/t:

$$\text{SOS}' = \text{SOS} (1+\delta) (1-\epsilon + o^2(\epsilon)) \tag{15}$$

$$= \text{SOS} (1 + \delta - \varepsilon + o^2(\varepsilon)) \quad (16)$$

This expression can be further reduced by rewriting ε in terms of δ :

$$\text{SOS}' = \text{SOS} (1 - ((w)(\delta)/\text{SOS}_{\text{pads}})/t + \delta + o^2(\delta)) \quad (17)$$

$$= \text{SOS} (1 + \delta (1 - \text{SOS}/\text{SOS}_{\text{pads}}) + o^2(\delta)) \quad (18)$$

Using this expression, a determination of how closely the speed of sound with squish compensation SOS' tracks the SOS can be made. For this determination only the first term is needed because it is the largest and because δ is very small, as noted above. Referring to the above illustration where a typical heel is about 33mm wide and the total squish of the pads is about 1mm, and that the difference between the squish when the pads touch and when the pads contact the body is about 0.5mm, then δ would equal about 0.5/33 or .015. If the coupling pads are made of a material having a value for SOS_{pads} which is in the approximate middle of the biological range of between about 1450 m/s and about 1670 m/s (e.g., 1560 m/s). As an example, if the patient was at 1450 m/s then $1 - \text{SOS}/\text{SOS}_{\text{pads}}$ would be about 0.076. As a result, SOS' will differ from SOS by about 0.11% (.015 \times 0.076 = 0.0011 or 0.11 %). Thus, the difference between SOS' and SOS is dependent on the $\delta(1 - \text{SOS}/\text{SOS}_{\text{pads}})$ term of the above expression.

[0084] As discussed above, the preferred way to determine the time t' and the width w' includes transmitting an ultrasound signal from one pad to the other when the pads are touching and measuring a first propagation time t_1 for the ultrasound signal to pass from one pad to the other. At the same time, the position encoder determines a first position ep_1 of the pads. A patient's body part, e.g., the heel, is then positioned between the coupling pads and an ultrasound signal is again transmitted between the pads. The ultrasound signal is measured and a second propagation time t_2 is determined. At the same time, the position encoder determines a second position ep_2 of the pads. The difference in propagation time measurements, i.e., $t_2 - t_1$, is used to determine the time t' it takes the ultrasound to pass through the patient's body. The difference in encoder positions, i.e., $ep_2 - ep_1$, is used to determine the width w' of the patient's body part. As discussed above, the encoder has a code strip mounted onto one transducer assembly and an optical encoder reader mounted on the other transducer assembly. The code strip moves in a slot in the optical encoder reader, and the optical reader reads lines of the code strip as the lines are traversed. Preferably, the number of lines traversed are converted to meters.

[0085] By using the encoder to measure the width w' of the body part, the determination of SOS' is self-adjusting because if the durometer of the pads change with age or temperature they will squish to a greater or lesser extent on both measurements so the difference will not substantially change.

[0086] An alternative technique for measuring SOS' according to the present application includes transmitting an ultrasound signal when the pads are touching and determining a propagation time t_3 for the ultrasound signal to pass through the pads. At the same time, a position of each transducer is determined and recorded as p_1 and p_2 . A patient's body part, e.g., the heel, is then positioned between the coupling pads and an ultrasound signal is again transmitted between the pads. The ultrasound signal is measured and a propagation time t_4 for the ultrasound signal to pass through the pads and body part is determined. At the same time, the position of each transducer is again determined and recorded as p_3 and p_4 . The position p_1 and p_3 relate to one transducer and positions p_2 and p_4 relate to the other transducer. The difference in propagation time measurements (i.e., $t_4 - t_3$) is used to determine the time t' it takes the ultrasound signal to pass through the body part.

[0087] The width w' of the body part with squish compensation is determined by determining a distance between positions p_1 and p_3 of the transducers and calculating a first width w_1 , and then determining a distance between positions p_2 and p_4 of the transducers and calculating a second width w_2 . The difference of the widths w_1 and w_2 is the width w' of the body part with squish compensation.

Transducer Pad Evaluation

[0088] The condition of the transducer coupling pads 102 and the time for transducer coupling pad replacement can be determined by performing SOS measurements. The transducer coupling pads are typically formed of a material, the characteristics of which will change over time. For example, as the pads age, the squish of the pads may increase or decrease. At some point, when the amount of squish is no longer tolerable, a determination can be made to replace the pads.

[0089] According to this feature, the periodic measurements performed on the apparatus for quality control measurements or calibration using the phantoms, can be used to determine the quality of the transducer pads. As described in the present specification, during measuring of the SOS , the width of the phantom is determined. That is, during each quality control or SOS calibration measurement utilizing the phantom, the width of the phantom is determined in order

to calculate SOS. The phantom width values can then be stored in memory 201 after each measurement. Periodic comparisons of the measured phantom width values can then be made by controller 200 to determine if the width of the phantom appears to have changed significantly. The phantom is made from a relatively rigid material compared to the material from which the transducer coupling pads are made. Accordingly, any substantial change in the measured width of the phantom can normally be attributed to a change in squish of the transducer coupling pads. For example, if over the course of time the width of the phantom appears to change (plus or minus) by more than a set amount from a pre-defined value, it may be desirable to change the pads. An indication can then be provided to the operator via display device 210 that the pads need to be replaced and the operator can then take appropriate action.

10 Other Provisions Related to Temperature

[0090] The present invention makes other provisions for controlling the environment of the transmission media.

[0091] Referring to Figs. 9A and 9B, the transducer assembly 110 includes a heater coil 291, a cap 292, and a housing 293. The heater coil 291 is wrapped around a portion of the coupling pad 150. The cap 292 isolates the heater coil 291 from the housing 293. Furthermore, a temperature sensor 294 (shown in Fig. 4) is buried inside the coupling pad 150, and thereby the temperature of the pad 150 can be monitored. The controller 200 monitors a temperature reading supplied by the temperature sensor 294 and controls the heater coil 291 accordingly to maintain the pads 150 at a predetermined temperature, such as approximately body temperature.

[0092] Referring to Fig. 10, the phantoms 260, 270 and 280 which are used for calibration or quality assurance according to the present invention are preferably also provided with respective heaters 267, temperature sensors 268 and controllers 269. The temperature sensor 268 are also buried inside the respective phantoms and supply readings of the respective temperatures of the respective phantoms. The controllers 269 monitor the respective temperature readings of the respective temperature sensors 268 and controls the respective heaters accordingly to maintain a predetermined value. For example, the temperature of the phantom can be maintained at approximately body temperature to simulate the measurement of the heel. The temperature at which an ultrasound measurement of the signal passing through one of the phantoms thereby can be controlled.

[0093] Coupling gel can be used with the phantoms of the present invention and for performing heel measurements. While the typical commercially available water-based coupling gel can be used, a non-aqueous jelly is preferred. That is, water-based coupling gels, although used effectively for qualitative imaging, cause a significant delay in pad-to-skin coupling, which can have a significant effect on quantitative ultrasound measurements. In other words, after application of the water-based gels, the acoustic coupling may change substantially over time. If measurements are made during this relatively unstable time, the measurements may be erroneous and unacceptable. For this reason, it is preferable that a petroleum jelly be used as the coupling gel as a coupling agent for both phantom and heel measurements. Preferably a petroleum jelly that does not exhibit the above-described time dependence properties is selected as the coupling gel.

[0094] The above embodiments have been described by using three separate phantoms. However, the relevant features of the respective phantoms can be combined into a single phantom. For example, the single phantom can have the configuration of one of the above-described phantoms, and includes combined materials to provide the above-described properties of the three phantoms so that a received signal that passed through the single phantom has signal characteristics corresponding to these properties.

Temperature Independent Ultrasonic Bone Analysis Apparatus and Systems

[0095] The next embodiment relates to an ultrasonic bone analysis apparatus that utilizes transducer pads having a temperature independent SOS. The overall arrangement for an ultrasonic bone analysis apparatus utilizing transducer pads which have temperature independent SOS according to the next embodiment, is similar to the embodiment depicted in Fig. 1 and includes a foot well assembly 3. As described above with respect to Fig. 1, the foot well assembly 3 includes a box cover 38 having a foot support 39, and foot well bottom 37. The foot support 39 has an area slightly larger than a human foot. Transducer ports 36 are located on the sides of the foot support 39, towards the rear. Bridge brackets 30 with respective channels 31 which are located along the sides of the foot support 39 facilitate the mounting of a shin guide assembly (not shown) for restraining the foot and lower leg.

[0096] According to this embodiment, the transducer assemblies differ from the above embodiment shown in Fig. 2. According to this embodiment as shown in Fig. 11, a transducer drive mechanism of the ultrasonic bone analysis apparatus includes a pair of transducer assemblies 300. The transducer assemblies 300 include respective transducers 301 and respective liquid-filled bladders 302.

[0097] The transducer assemblies 300 are mounted to respective carriages 303 that slide along a lateral-medial axis. The carriages 303 are provided with sufficient freedom of movement such that respective liquid-filled bladders 302 can be brought into mutual contact. Respective compression springs 304 attached to the carriages 303 apply opposing

lateral forces towards the center of the foot. The carriage/spring assembly is free floating and will center itself on the foot with equal pressure on both sides.

[0098] An extension spring 305 applies the initial pressure when the liquid-filled bladders 302 reach the patient's foot. To adjust the pressure in small increments, a stepper motor with rack and pinion mechanism 306 will move a finite number of steps and compress the compression springs 304 that are attached to the respective carriages 303. The compression springs 304 will pull the respective transducers 301 and bladders 302 inward at a force proportional to the spring rate and distance translated.

[0099] According to the embodiment shown in Fig. 11, liquid filled bladders 302 include a deformable cover (or membrane) 307. The cover is filled with an acoustic coupling material 308. The acoustic coupling material 308 is preferably a mixture of materials, the combination of which has a substantially zero temperature coefficient of sound propagation over a large range of temperatures. That is, the sound propagation through coupling material 308 should not vary substantially with temperature. An example of a mixture having such properties that can be used as the coupling material 308 is a water and ethyl alcohol mixture, the mixture being 17% ethyl alcohol by weight.

[0100] According to this embodiment, since the SOS of the coupling material 308 is temperature independent, a temperature correction term is not necessary. Preferably, the acoustic coupling medium has an SOS close to the SOS of a typical patient's heel. For example, the water, ethyl alcohol mixture has a SOS substantially close enough to that of the average patient's heel, so that the amount of squish of the pads can be ignored as described above.

[0101] According to yet another embodiment shown in Fig. 12, respective transducer assemblies 315 are coupled and mounted to fixed frame 314. Transducer assemblies 315 include respective transducers 301, respective acoustical delay lines 309 and respective fillable bladders 312.

[0102] Pumps 311 are provided for pumping the acoustic coupling fluid 319 from respective storage tanks or bladders 310 to respective fillable bladders 312. As shown by solid lines in Fig. 12, when bladders 312 are not filled, a patient's heel 320 can be easily positioned there-between. After positioning of the patient's heel, fluid can be pumped via pumps 311 from respective storage bladders 310 to respective fillable bladders 312. As shown by dotted lines, when filled, fillable bladders 312 substantially conform to the contour of the patient's heel 320. SOS and BUA measurements can then be performed on the patient. After all measurements have been performed, the pumps 311 are reversed and the fluid is pumped from fillable bladders 312 back into storage bladders 310 and the patient's heel 320 can be removed.

[0103] According to this embodiment, the acoustic coupling fluid 319 is preferably a mixture of materials having a substantially zero temperature coefficient of sound propagation over a large range of temperatures. For example, a water, ethyl alcohol mixture as described in the previous embodiment can be used.

Temperature Independent Wet System

[0104] The next embodiment relates to a wet system. As shown in Fig. 13, the wet system includes a foot well assembly 400. The foot well assembly 400 includes a box cover 401 having a foot support 402, and a foot well bottom 403. The foot support 402 has an area slightly larger than a human foot. Fixed transducers 406 are located on the sides of the foot support 402, towards the rear. Bridge brackets 405 with respective channels 404 can be located along the sides of the foot support 402 to facilitate mounting of a shin guide assembly (not shown) for restraining the foot and lower leg.

[0105] As shown in Fig. 14, a patient's heel 410 is positioned on foot well bottom 403 in a liquid 411. Liquid 411 is preferably a mixture of materials, the combination of which has a substantially zero temperature coefficient of sound propagation over a large range of temperatures such as, for example, a water, ethyl alcohol mixture with 17% ethyl alcohol by weight.

[0106] In each of the described embodiments, the coupling fluid mixture has been described as a water, ethyl alcohol mixture. Of course, other combinations are possible, with the ultimate goal being to provide a coupling medium which has a zero temperature coefficient of sound propagation over a large range of temperatures.

[0107] In a typical "wet system" water is used as the acoustic coupling medium for coupling the signal between two fixed transducers. However, since the SOS through water is highly temperature dependent, the measurements of the patient's heel will vary considerably based on temperature. Accordingly, typical wet systems employ a water heater in the system for heating the water to a predefined temperature having a predetermined SOS. However, these systems are more costly to produce and operate because of the heater requirement. In addition, since the patient's body temperature can effect the temperature of the water when the patient's body part is inserted, the accuracy of the measurements may suffer.

[0108] In a wet system, to determine the SOS through a patient's heel, several measurements are required. The first measurement measures the SOS through just the water. The measured time that the signal takes to travel between the sending transducer and the receiving transducer can be expressed:

(19)

$$t_{H_2O} = \frac{W_L}{SOS_{H_2O}(T)} + offset$$

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10 **[0109]** Where W_L is the width or distance between the transducers, $SOS_{H_2O}(T)$ is the SOS through water at a temperature T and $offset$ is an arbitrary offset required for variations in the accuracy of the electronic components.

[0110] A patients heel is then placed in the apparatus and the SOS through the patients heel is measured. The time through the patients heel can be expressed:

$$t_{heel} = \frac{W_L}{SOS_{H_2O}(T)} - \frac{W_{heel}}{SOS_{H_2O}(T)} + \frac{W_{heel}}{SOS_{heel}} + offset$$

15

20

From the equations 19 and 20, Δt is derived:

(21)

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$$\Delta t = t_{heel} - t_{H_2O} = \frac{W_{heel}}{SOS_{heel}} - \frac{W_{heel}}{SOS_{H_2O}(T)}$$

30

Solving for SOS_{heel} :

35

$$SOS_{heel} = \frac{W_{heel}}{\frac{W_{heel}}{SOS_{H_2O}(T)} + \Delta t}$$

(22)

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[0111] Accordingly, it is seen that since temperature T may not be known or may vary, the accuracy of the SOS measurements will be effected.

45 **[0112]** However, according to this embodiment, the liquid used as the acoustic coupling medium has a predetermined SOS which is substantially temperature independent. Accordingly, the measurements can be more accurately performed over substantially any range of temperatures.

Other Provisions Related to Temperature

50 **[0113]** The present invention makes provisions for a coupling fluid through which the speed at which sound travels does not vary significantly with temperature. The advantage of using such a fluid is that the distance between the transducers does not need to be known, and no distance calibration needs to be done. By mixing the correct ratio of fluids that have opposite temperature coefficients, it is possible to produce a fluid that has a constant SOS over a range of temperatures. It is possible then to mix a combination of fluids such that when they are combined the SOS of the solution is at the clinical threshold value for healthy or osteoporotic bone. This allows for a simple screening algorithm to detect osteoporotic bone: if the time for the ultrasonic sound to go through the liquid is longer with the patient's heel in the path, then the patient is osteoporotic. Conversely, if the subject's heel caused sound to traverse the path between the transducers more quickly than when there was only solution, then the subject would be considered healthy.

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[0114] Having described the present invention with reference to the accompanying drawings, it is to be understood that the invention is not limited to that precise embodiment and that various changes and modifications thereof could be effected by one skilled in the art without departing from the spirit or scope of the novel concepts of the invention, as defined in the appended claims.

5

Claims

1. A method of calibrating an ultrasound bone analysis apparatus having a plurality of transducer assemblies with a respective plurality of transducers and a respective plurality of coupling pads and measuring a SOS of a body part, comprising:

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providing a plurality of coupling pads having a SOS substantially similar to the SOS of the body part to be analyzed:

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adjusting the plurality of transducer assemblies until the plurality of coupling pads are mutually in contact, the plurality of coupling pads mutually contacting each other using a first amount of pressure;

transmitting an ultrasound signal through one of the plurality of transducers;

receiving a signal corresponding to the transmitted signal through another one of the plurality of transducers;

determining a first propagation time of the transmitted signal and a first position of the transmitting and receiving transducers;

20

positioning a body part between the plurality of coupling pads, the coupling pads contacting the body part using a second amount of pressure different than the first amount of pressure;

transmitting an ultrasound signal through the transmitting transducer;

receiving a signal corresponding to the transmitted signal through the receiving transducer;

determining a second propagation time of the transmitted signal and a second position of the transmitting and receiving transducers; and

25

determining a time for the ultrasound signal to pass from the transmitting transducer to the receiving transducer based on the first and second propagation times and a width of the body part based on the first and second positions.

30 2. A method as recited in claim 1, wherein said step of positioning a body part between the plurality of coupling pads includes applying a non-aqueous gel between the body part to be analyzed and the coupling pads.

3. A method of calibrating an ultrasound bone analysis apparatus and measuring a SOS of a body part, comprising:

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providing a pair of ultrasound transducer assemblies each having a transducer and a coupling pad, the transducer assemblies being movable between a first position where a face of each coupling pad are in contact at a first pressure and a second position where the face of each coupling pad are coupled to a body part at a second pressure different than the first pressure;

40

transmitting an ultrasound signal from one transducer and receiving a signal corresponding to the transmitted ultrasound signal through the other transducer when the transducer assemblies are in the first position and the second position;

determining a time for the ultrasound signal to pass through the body part;

determining a width of the body part based on positions of the transducers; and

calculating a speed of sound of the ultrasound signal passing through the body part using the time for the ultrasound signal to pass through the body part and the width of the body part such that the calculation of the speed of sound includes compensation for squish of the

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50 4. A method of calibrating an ultrasound bone analysis apparatus having at least a pair of transducer assemblies, each transducer assembly having a transducer and a coupling pad and measuring a SOS of a body part, comprising the steps of:

selectively transmitting an ultrasound signal from at least one of the transducers and receiving a signal corresponding to the transmitted ultrasound signal through at least one of the transducers when a face of each pad are in mutual contact at a first pressure and when a body part is positioned between the coupling pads at a second pressure different than the first pressure;

55

determining a time for the ultrasound signal to pass from the at least one transmitting transducer to the at least one receiving transducer when the ultrasound signal is selectively transmitted;

determining a time for the ultrasound signal to pass through the body part using the times for the ultrasound

signal to pass from the at least one transmitting transducer to the at least one receiving transducer;
determining a position of each transducer when the ultrasound signal is selectively transmitted;
determining a width of the body part using the positions of the transducers; and
calculating a speed of sound of the ultrasound signal passing through the body part using the time for the ultra-
sound signal to pass through the body part and the width of the body part such that the calculation of the speed
of sound includes compensation for squish of the pads.

5. A method for calibrating an ultrasound bone analysis apparatus having a plurality of transducer assemblies, each transducer assembly having a transducer and a coupling pad and measuring a SOS of a body part, comprising the steps of:

adjusting the transducer pads until a face of each pad are mutually in contact at a first pressure;
transmitting an ultrasound signal from one transducer and receiving a signal corresponding to the transmitted ultrasound signal through at least one of the plurality of transducers;
determining a first time associated with passage of the ultrasound signal from the transmitting transducer to the at least one receiving transducer and determining a first position of each transducer;
positioning a body part between the pads and pressing the face of each pad against the body part at a second pressure different than the first pressure;
transmitting an ultrasound signal from the transmitting transducer and receiving a signal corresponding to the transmitted ultrasound signal through the at least one receiving transducer;
determining a second time associated with passage of the ultrasound signal through the transducers and the body part and determining a second position of each transducer;
determining a time for the ultrasound signal to pass through the body part using the first and second times;
determining a width of the body part using the first and second positions of the transducers; and
calculating a speed of sound of the ultrasound signal passing through the body part using the time for the ultrasound signal to pass through the body part and the width of the body part such that the calculation of the speed of sound includes compensation for squish of the pads.

6. A method for calibrating an ultrasound bone analysis apparatus, said method comprising:

providing a phantom having a frequency attenuation approximating a body part to be analyzed and having a predetermined speed of sound (SOS) and broadband ultrasound attenuation (BUA) measured at a predefined temperature;
calibrating the ultrasound bone analysis apparatus at an arbitrary temperature,
said calibration comprising;
adjusting the plurality of transducer assemblies so that the plurality of coupling pads are mutually in contact;
transmitting an ultrasound signal through one of the plurality of transducers;
receiving a signal corresponding to the transmitted signal through another one of the plurality of transducers;
determining a first propagation time of the transmitted signal and a first position of the transmitting and receiving transducers;
positioning the phantom between the plurality of coupling pads so that the coupling pads contact the phantom;
transmitting an ultrasound signal through the transmitting transducer;
receiving a signal corresponding to the transmitted signal through the receiving transducer;
determining a second propagation time of the transmitted signal and a second position of the transmitting and receiving transducers;
determining a SOS of the ultrasound signal passing from the transmitting transducer to the receiving transducer based on the first and second propagation times and a width of the phantom based on the first and second positions;
comparing the determined SOS to the predetermined SOS of the phantom and based on the result of the comparison, determining an amount of change in BUA of the phantom; and
storing in memory a BUA reference curve and an additive constant based on the result of the comparison.

7. A method as recited in claim 6, wherein said step of positioning the phantom between the plurality of coupling pads includes applying a non-aqueous gel between the phantom and the coupling pads.

8. A method as recited in claim 6, wherein said additive constant includes a correction term derived from the result of the comparison performed in the comparison step.

9. A method as recited in claim 6, wherein said additive constant includes the predetermined BUA measured at the predefined temperature.

5 10. A method of performing a quality control evaluation on an ultrasound bone analysis apparatus, said method comprising:

10 determining a direction of change in BUA of a phantom by measuring a signal through the phantom and calculating BUA of the phantom and comparing to a previously determined BUA value for the phantom;
determining a direction of change in SOS of the phantom by measuring a signal through the phantom and calculating based thereon SOS through the phantom and comparing to a previously determined value for the phantom;
evaluating, based on the results of the determinations of the directions of change of the BUA and SOS, a condition of the apparatus.

15 11. A method as recited in claim 10, wherein the evaluating step comprises determining if the directions of change in SOS and BUA are in the same directions.

20 12. A method as recited in claim 11, wherein if the directions of change in SOS and BUA are not in the same directions, a malfunction of the apparatus is indicated to an operator.

25 13. A method of evaluating parts of an ultrasonic bone analysis apparatus, comprising:

performing quality control evaluations or calibration measurements on the apparatus utilizing a phantom, wherein during the evaluations or measurements, a width of the phantom is measured;
at least periodically storing the measured width of the phantom;
periodically comparing a measured width of the phantom to a stored width of the phantom;
determining, based on the comparison, a variation in squish of the transducer pads; and
evaluating a condition of the transducer pads based on the determination.

30 14. A transducer assembly for use in an ultrasound bone analysis apparatus, said transducer assembly comprising:

a plurality of transducers;
a plurality of coupling pads each of which covers at least a portion of a corresponding one of the plurality of transducers; and
35 an acoustic coupling material provided between the transducer and the respective coupling pad, the acoustic coupling material comprising a material having a temperature independent speed of sound.

40 15. A transducer assembly as recited in claim 14 wherein the acoustic coupling material has a substantially zero temperature coefficient of sound propagation over a large range of temperatures.

45 16. A transducer assembly as recited in claim 14, wherein the acoustic coupling material comprises a water and ethyl alcohol mixture, the mixture being 17% alcohol by weight.

50 17. An ultrasound bone analysis apparatus comprising:

a pair of transducer assemblies, each comprising a transducer, a coupling pad which covers at least a portion of the transducer and an acoustic coupling material provided between the transducer and the respective coupling pad, the acoustic coupling material comprising a material having a temperature independent speed of sound;
55 a time measuring device for measuring a propagation time of ultrasound based on a signal transmitted between said transducers;
a distance measuring device for measuring at least one of a distance between the transducers and a width of a body part to be analyzed; and
a processor for determining a speed of sound of a body part to be analyzed based on the measurements performed by said time measuring device and said distance measuring device.

18. An ultrasound bone analysis apparatus as recited in claim 17, further comprising a unit for moving the transducer assemblies between various positions, including a position in which the coupling pads contact each other and a

position in which the coupling pads contact a body part to be analyzed.

5
19. An ultrasound bone analysis apparatus as recited in claim 18, wherein the acoustic coupling material has an SOS substantially similar to that of a body part to be analyzed.

10
20. An ultrasound bone analysis apparatus as recited in claim 19, further comprising biasing units for biasing the pair of transducer assemblies such that the biasing units bias the coupling pads against each other at a first pressure and bias the coupling pads against the body part to be analyzed at a second pressure different than the first pressure.

15
21. An ultrasound bone analysis apparatus comprising:

a container for containing an acoustic coupling material and capable of containing at least a portion of a body part to be analyzed within the acoustic coupling material, the acoustic coupling material comprising a material having a temperature independent speed of sound;

a pair of transducer assemblies, each comprising a transducer, each of said transducer assemblies being arranged on opposite sides of said container for transmitting and receiving ultrasound;

a time measuring device for measuring a propagation time of ultrasound based on a signal transmitted between said transducers; and

20
a processor for determining a speed of sound of a body part to be analyzed based on the measurements performed by said time measuring device.

25
22. An ultrasound bone analysis apparatus as recited in claim 21, wherein the acoustic coupling material has a substantially zero temperature coefficient of sound propagation over a large range of temperatures.

23. An ultrasound bone analysis apparatus as recited in claim 21, wherein the acoustic coupling material comprises a water and ethyl alcohol mixture, the mixture being 17% alcohol by weight.

30
24. A method of performing an ultrasound bone analysis on a body part to be analyzed, said method comprising:

positioning the body part to be analyzed between a pair of transducer assemblies, with a non-aqueous gel provided therebetween;

transmitting an ultrasound signal through one of the plurality of transducer assemblies;

35
receiving a signal corresponding to the transmitted signal through another one of the plurality of transducer assemblies; and

analyzing characteristics of the body part using the received signal.

25. A method for calibrating an ultrasound bone analysis apparatus, said method comprising:

40
performing measurements on a phantom to determine a speed of sound (SOS) of the phantom;

comparing the determined SOS to a predetermined SOS of the phantom measured at a predefined temperature and based on the result of the comparison, determining an amount of change in BUA of the phantom; and storing in memory a BUA reference curve and an additive constant based on the result of the comparison.

45
26. A method of operating a bone analysis apparatus comprising first and second transducers, the method comprising transmitting an ultrasound signal from the first transducer to the second transducer at first and second sets of transmission conditions, and determining the value of a parameter associated with the propagation of ultrasound signals on the basis of the ultrasound signal transmissions at the first and second sets of transmission conditions.

50

55

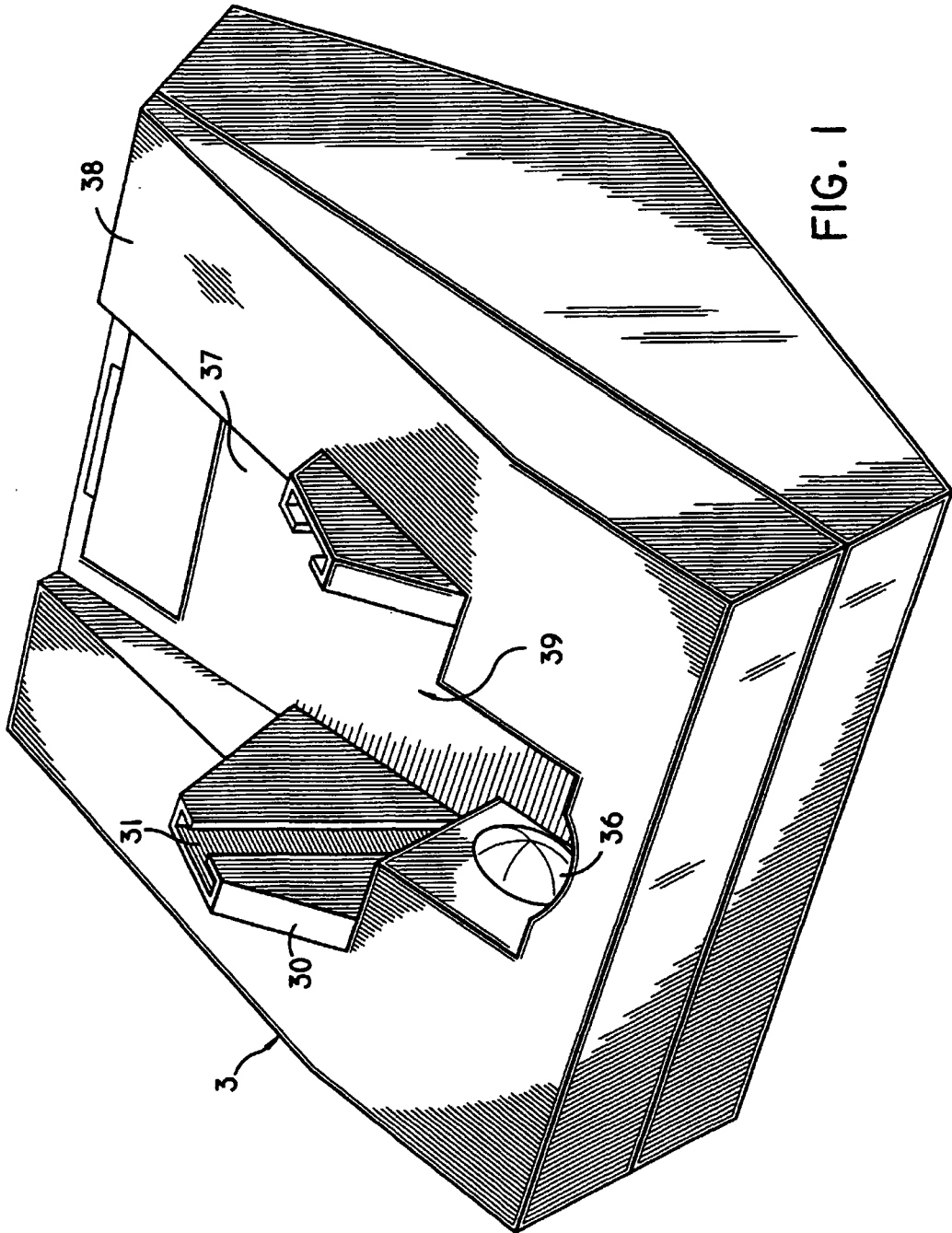
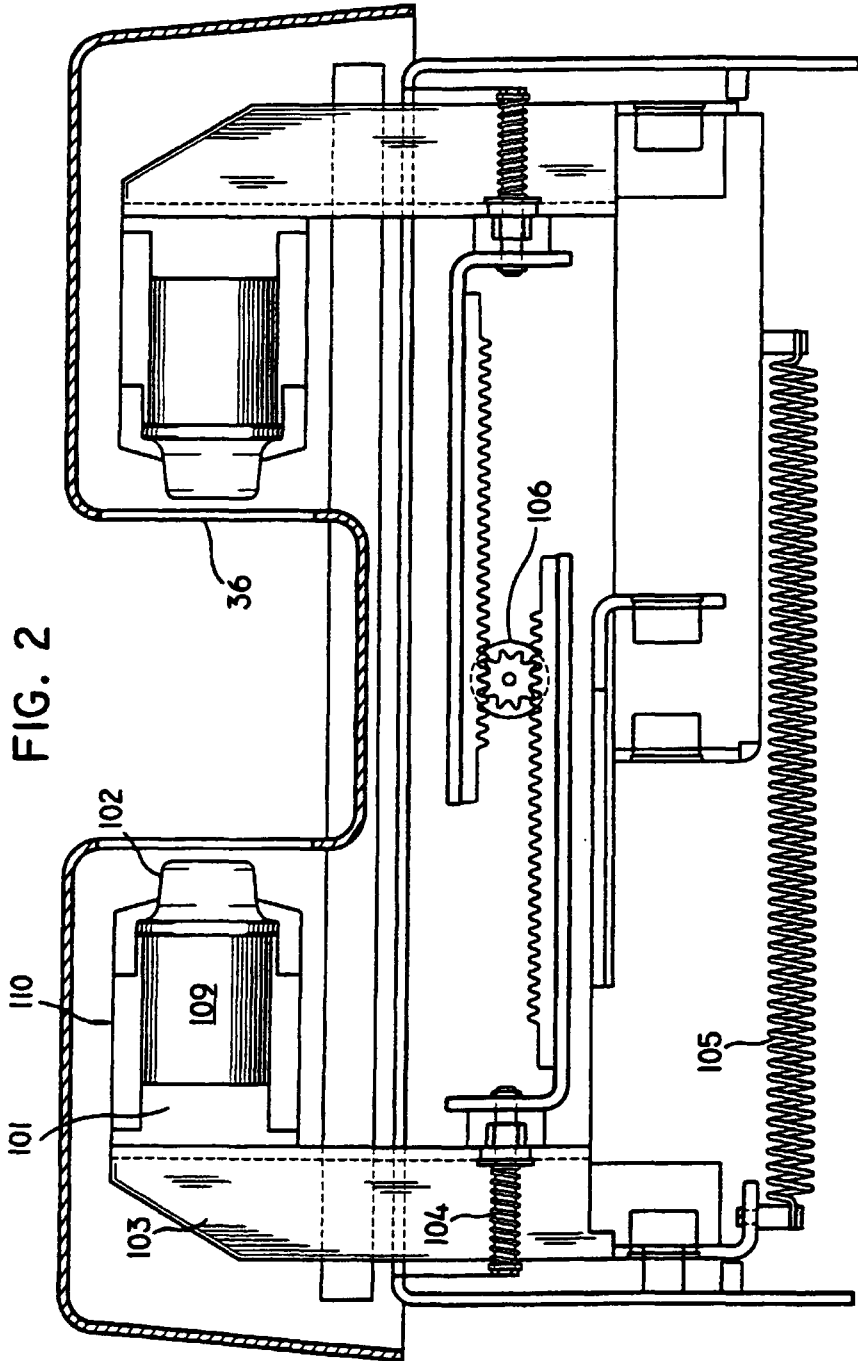


FIG. 1



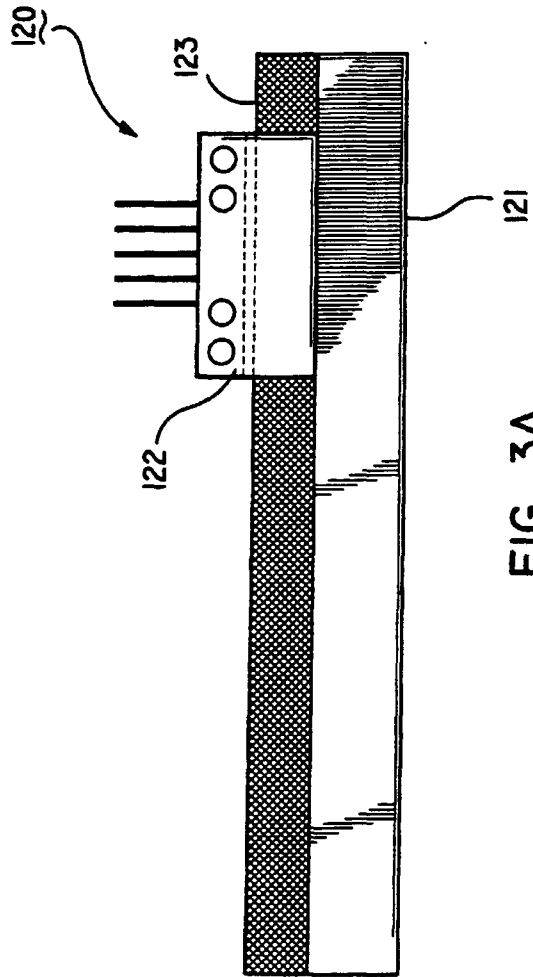


FIG. 3A

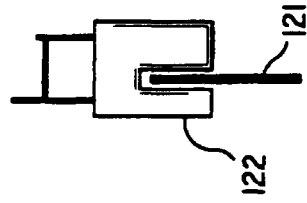


FIG. 3B

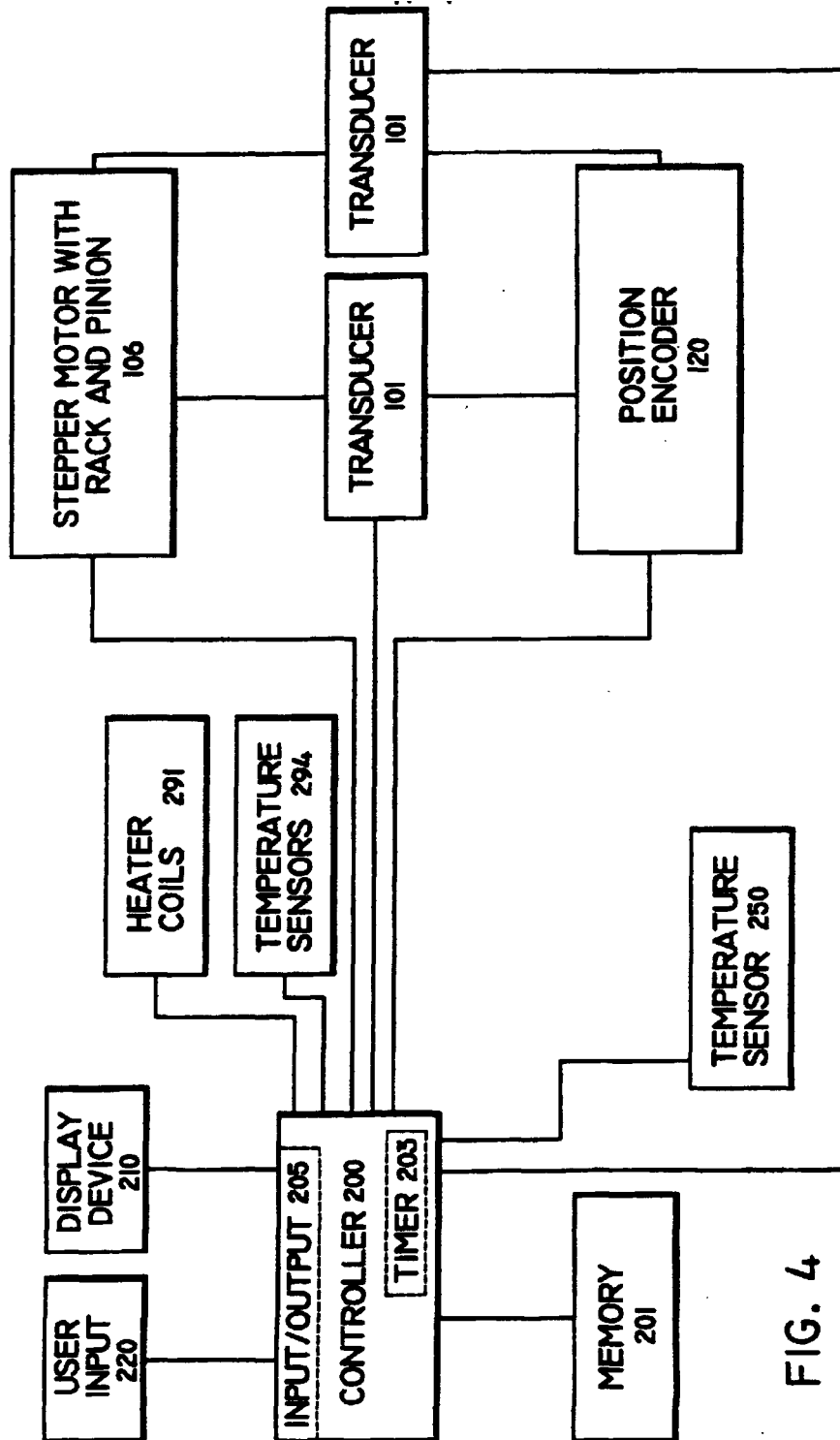
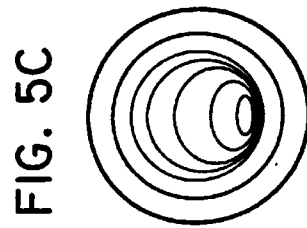
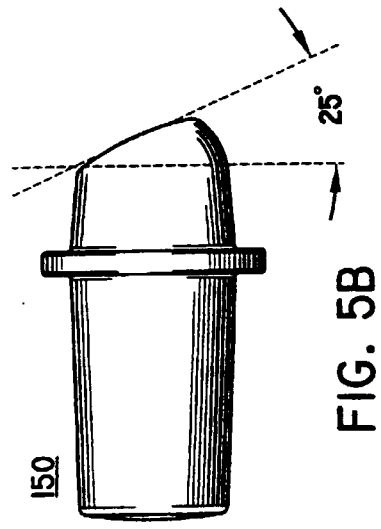
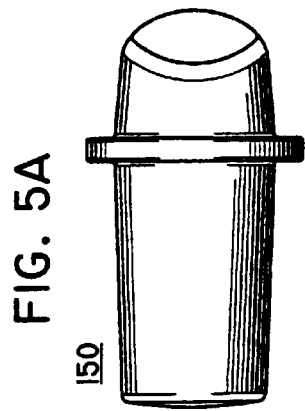


FIG. 4



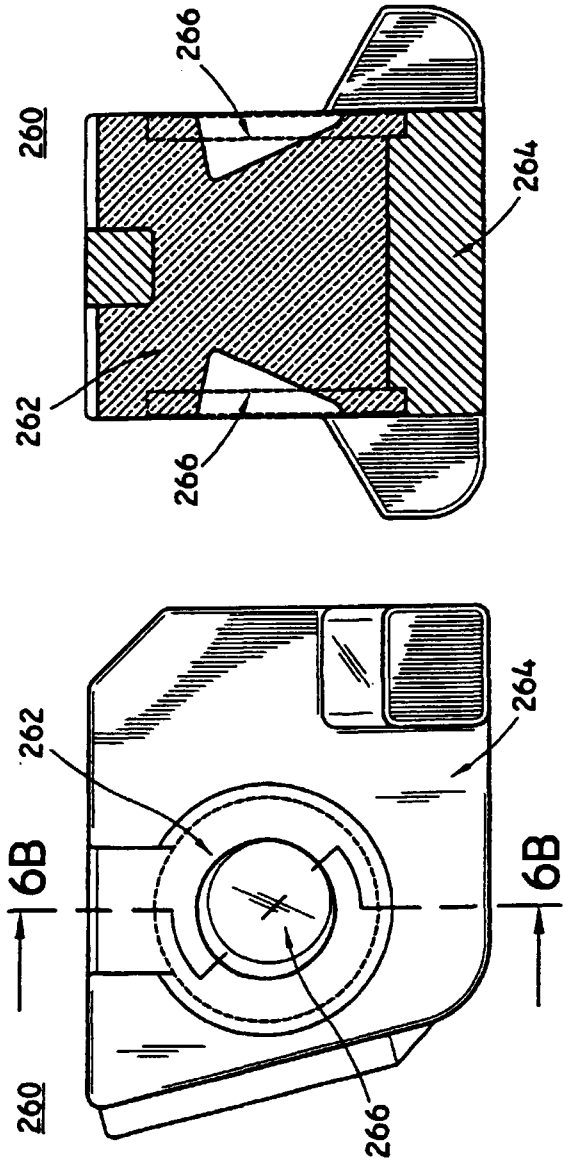


FIG. 6B

FIG. 6A

FIG. 7A

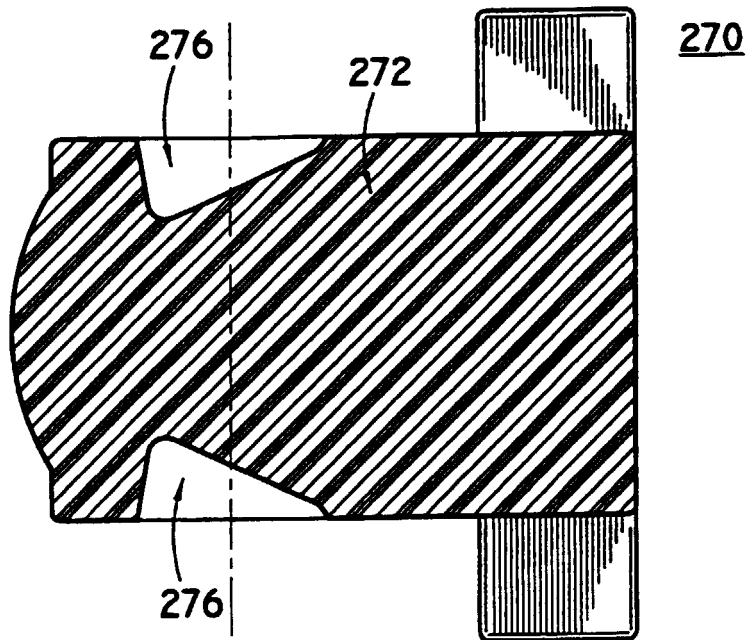
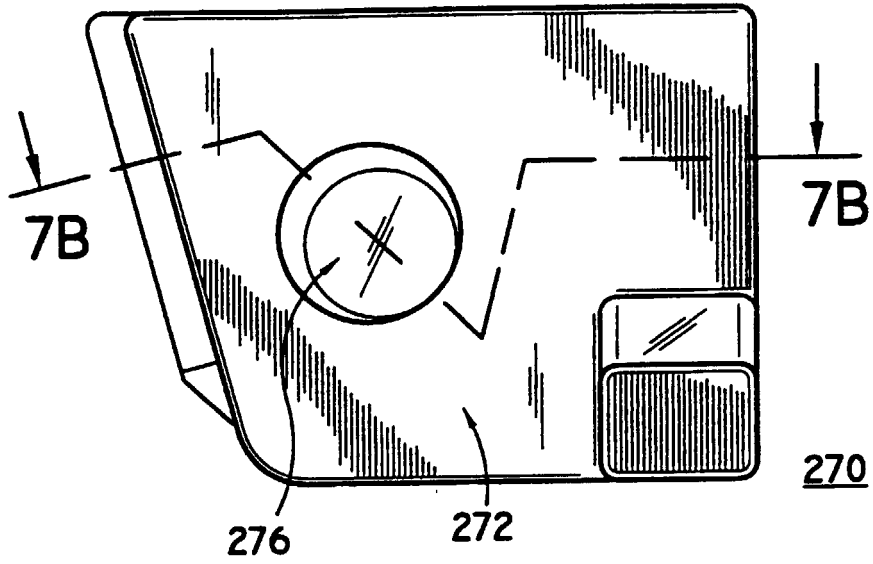


FIG. 7B

FIG. 8A

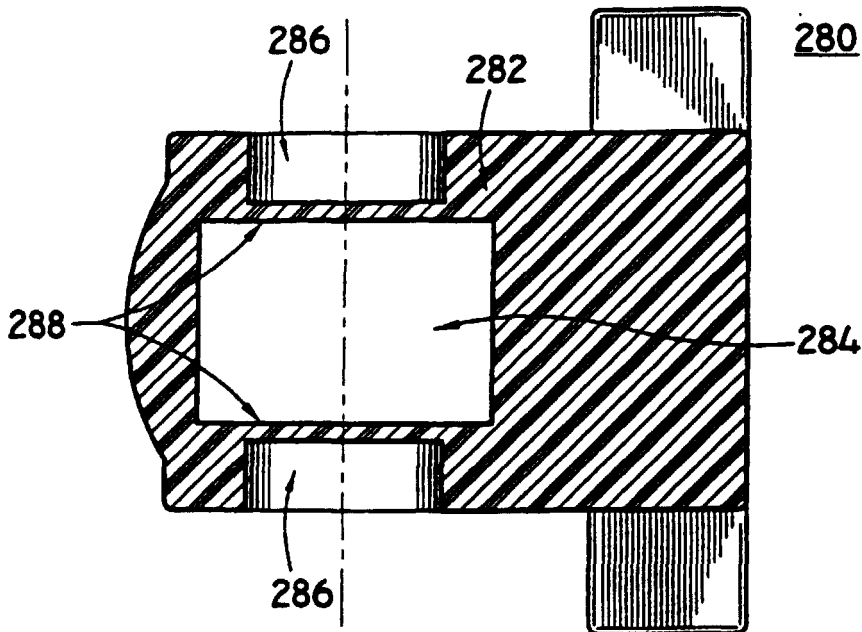
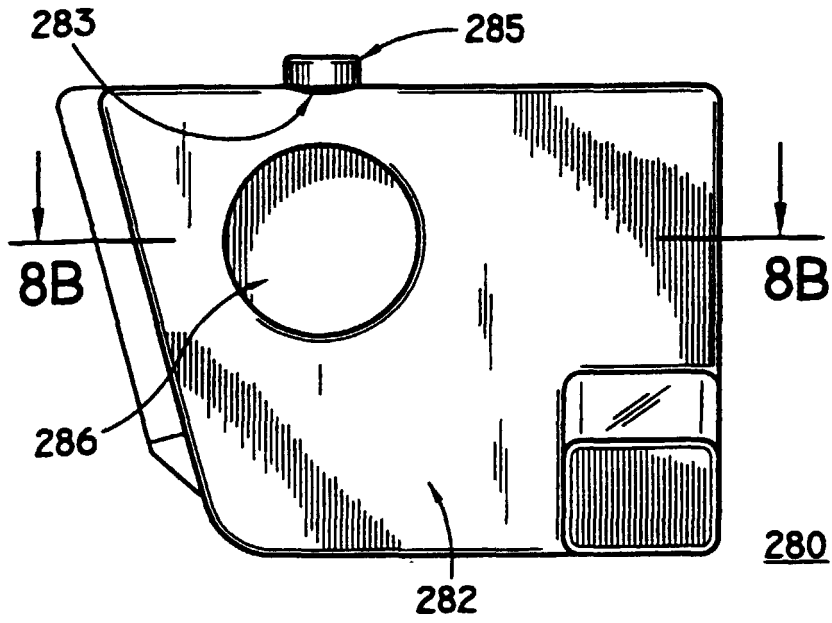


FIG. 8B

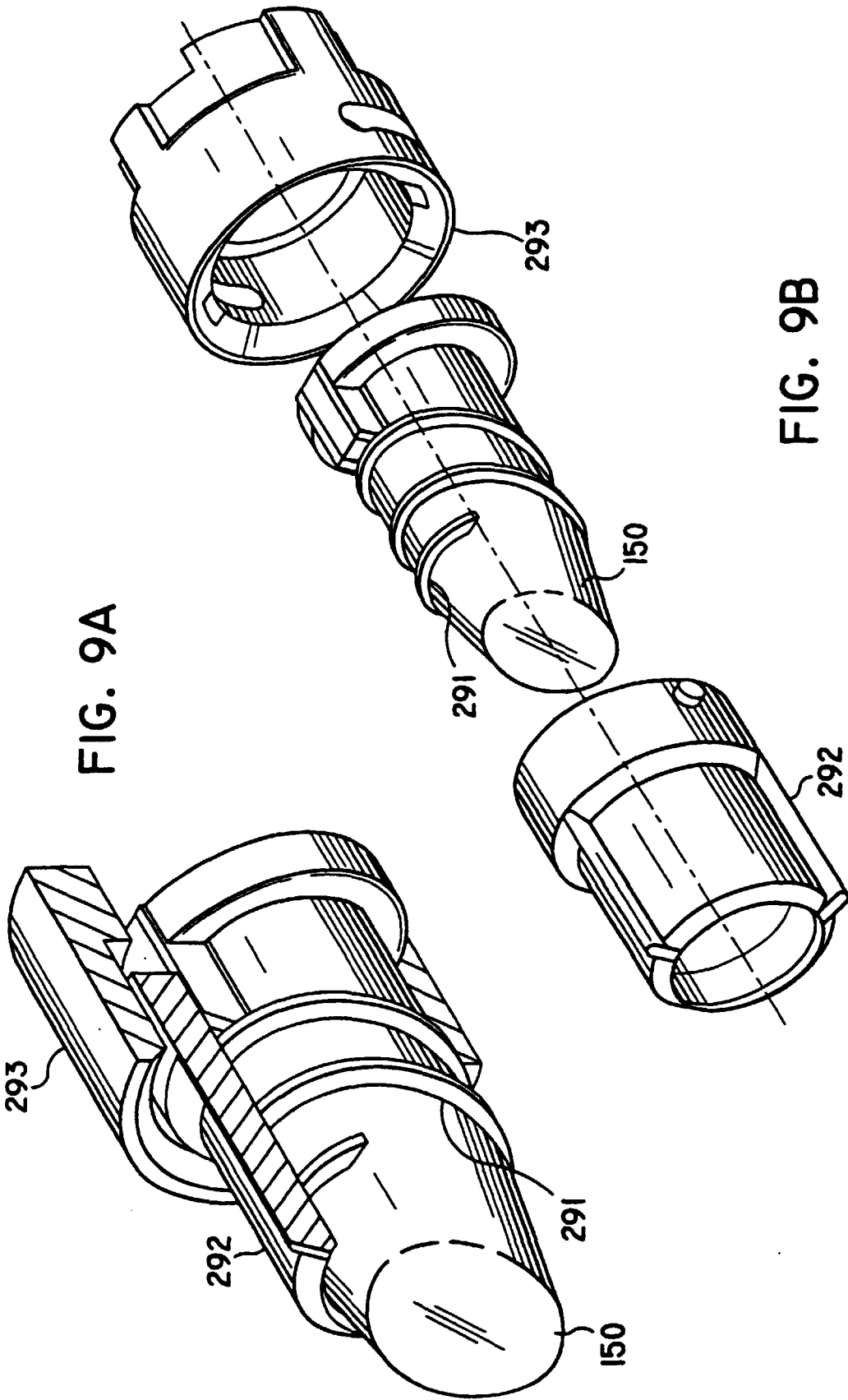


FIG. 9A

FIG. 9B

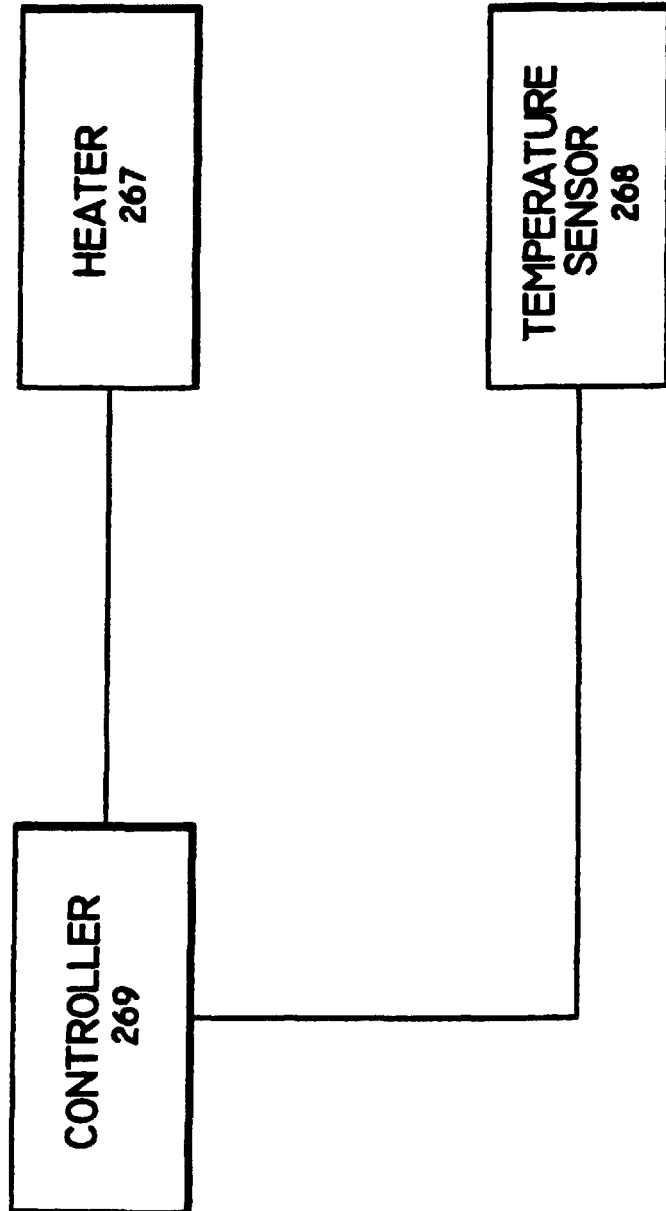


FIG. 10

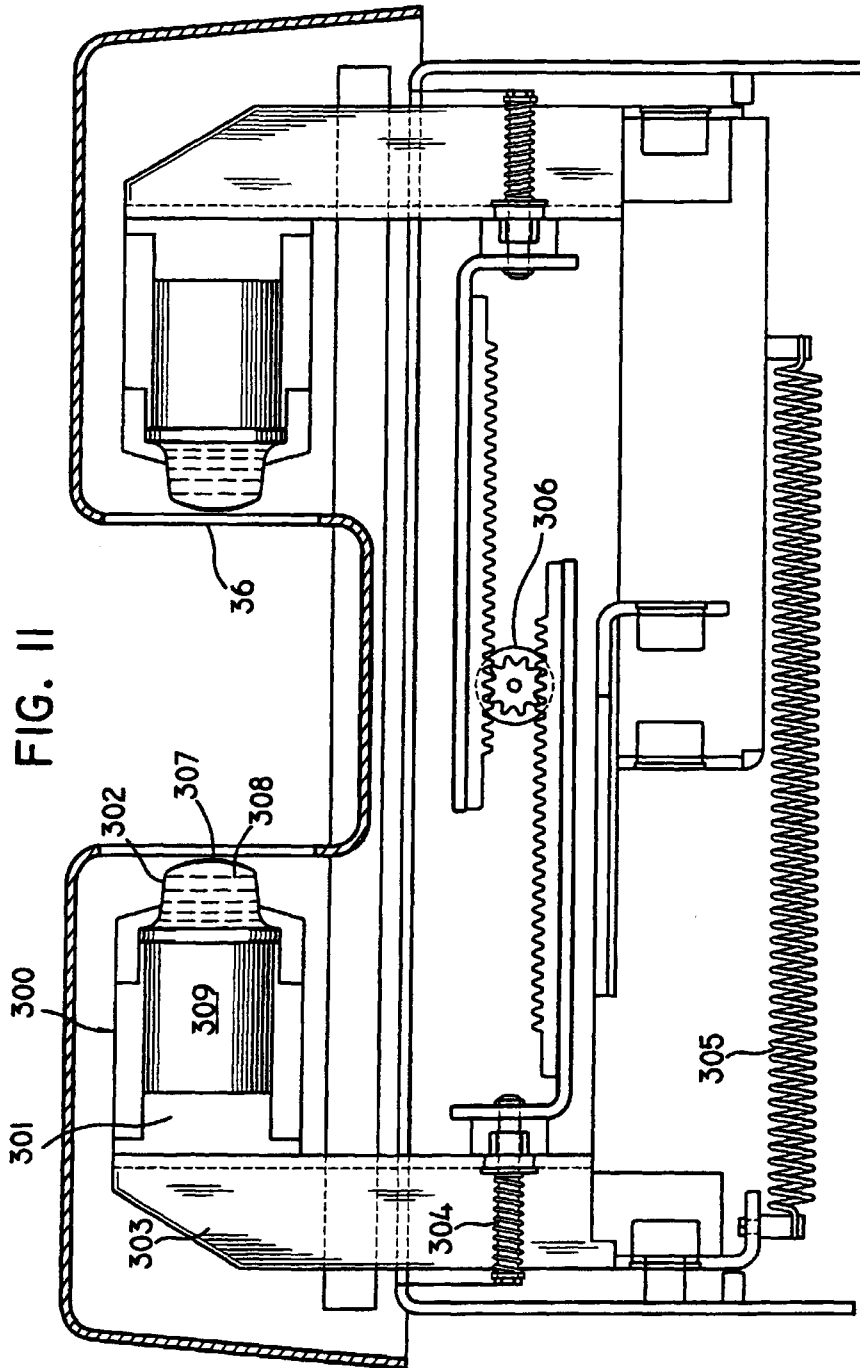
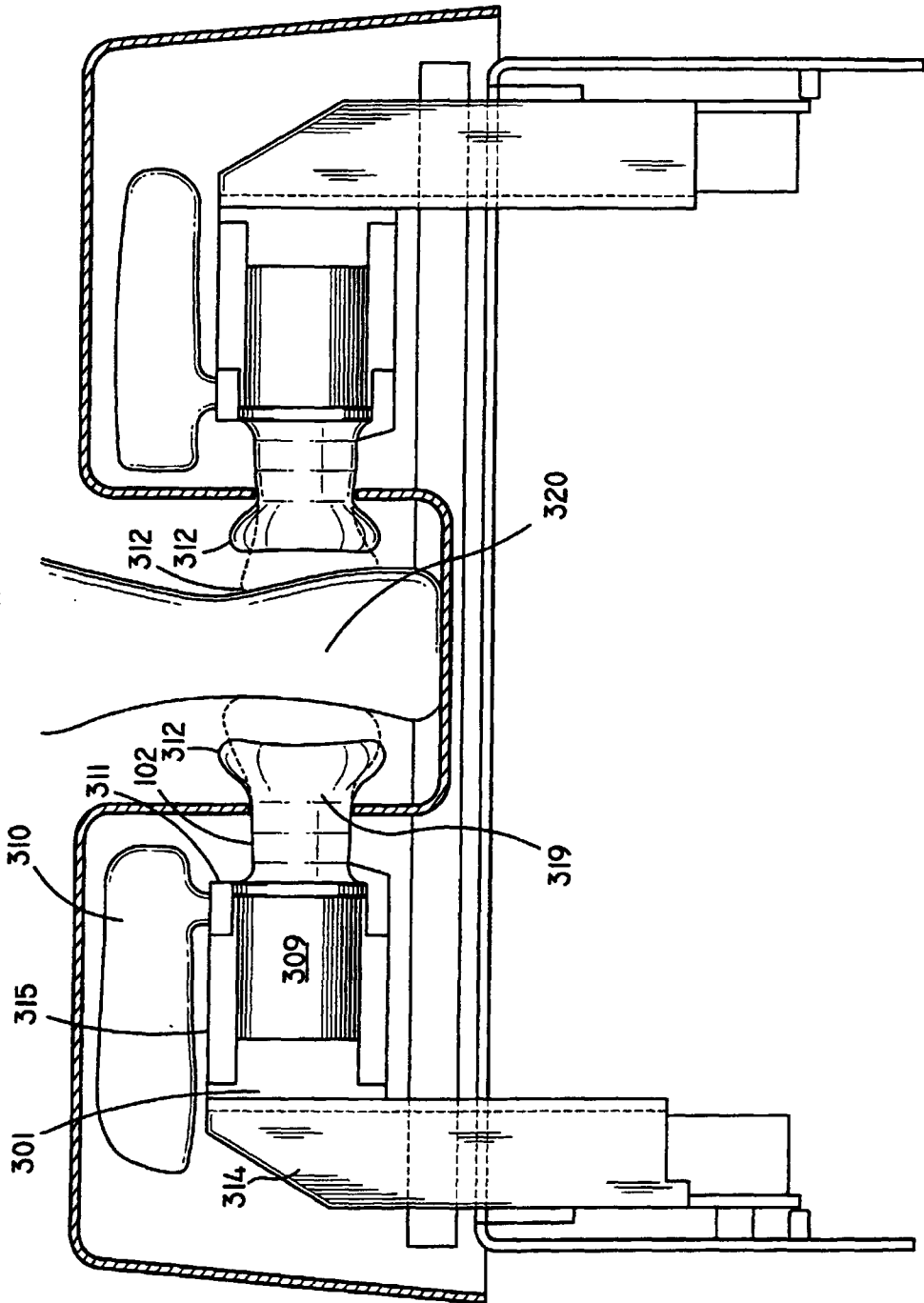


FIG. 12



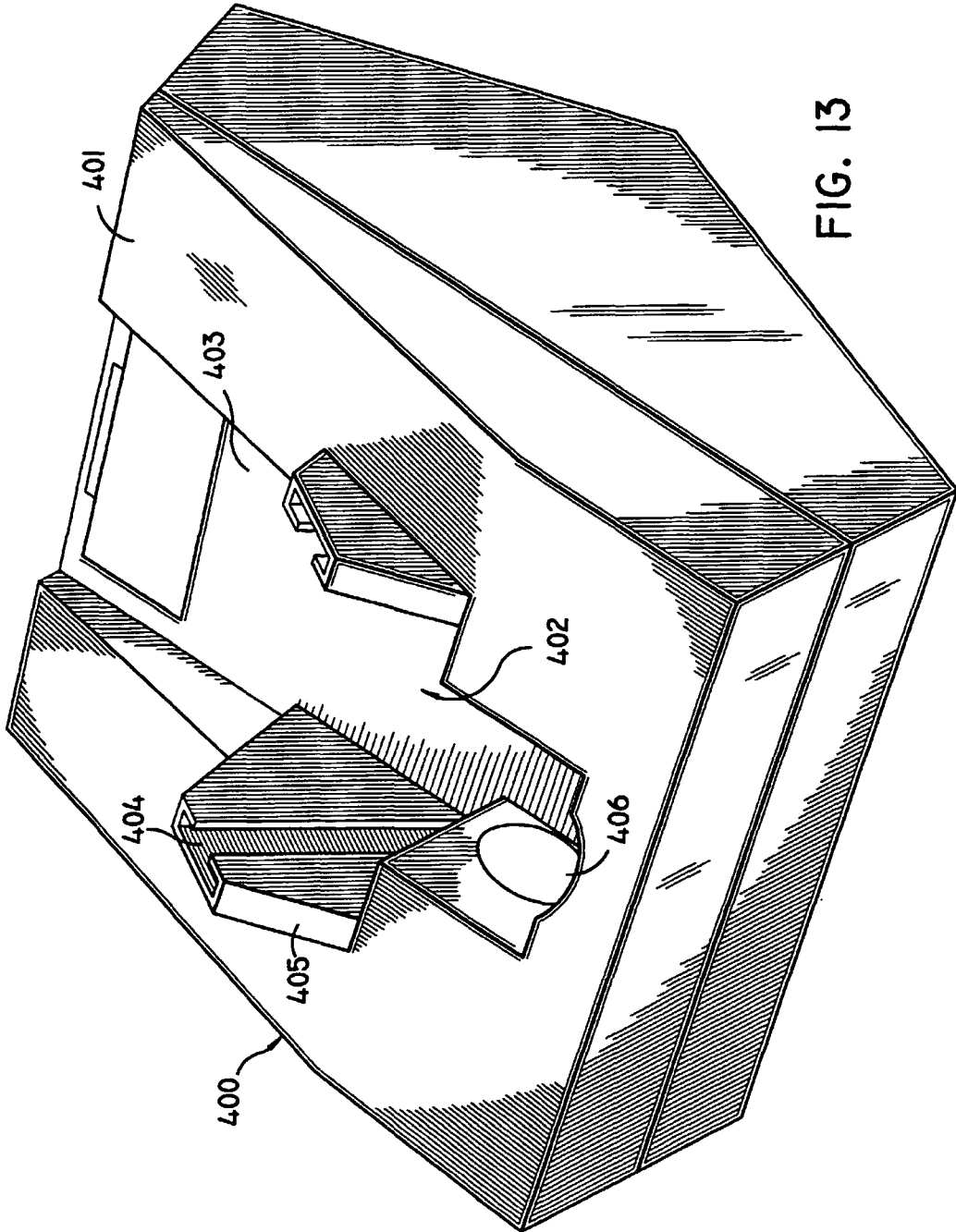


FIG. 13

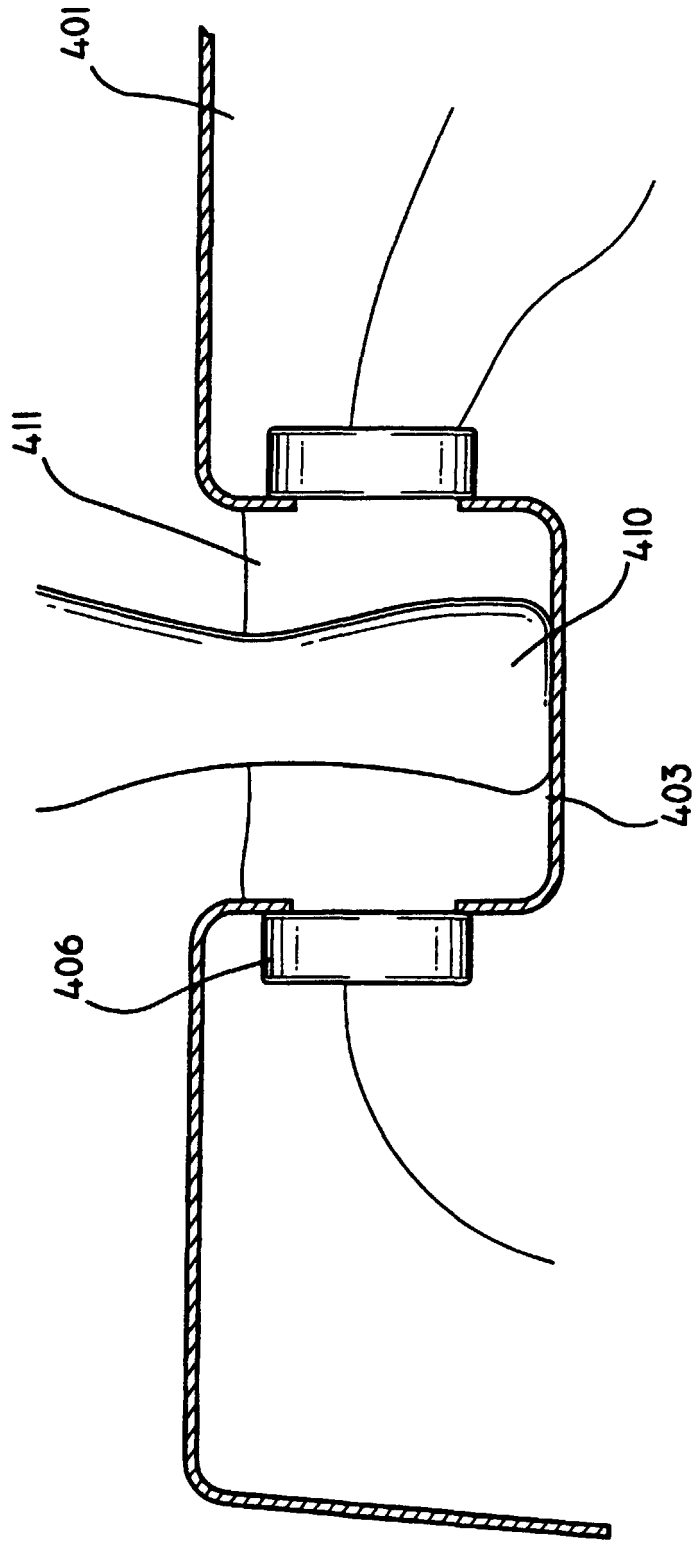


FIG. 14



European Patent
Office

EUROPEAN SEARCH REPORT

Application Number
EP 00 30 2476

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X	EP 0 765 635 A (HOLOGIC INC) 2 April 1997 (1997-04-02)	1-5, 16-19, 21,23,24	A61B8/08
A	* column 2, line 40 - column 4, line 46; tables 1-10 * * column 5, line 30 - column 13, line 39 *	14,15, 25,26	
A	EP 0 576 217 A (MCCUE ULTRASONICS LTD) 29 December 1993 (1993-12-29) * column 8, line 2 - line 46 * * column 11, line 31 - column 12, line 37; table 6 *	3	
A	EP 0 719 520 A (ALOKA CO LTD) 3 July 1996 (1996-07-03) * column 5, line 46 - column 16, line 7; tables 1-12 *	1,3-6, 17-21	
P,D, X	US 5 935 073 A (STEIN JAY A ET AL) 10 August 1999 (1999-08-10)	1-5,13, 16-19, 21,23,24	
A	* column 3, line 26 - column 12, line 5; tables 1-10 * -----	14,15, 25,26	TECHNICAL FIELDS SEARCHED (Int.Cl.7) A61B
The present search report has been drawn up for all claims			
Place of search BERLIN		Date of completion of the search 3 July 2000	Examiner Weihs, J
<p>CATEGORY OF CITED DOCUMENTS</p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons</p> <p>& : member of the same patent family, corresponding document</p>			

EPO FORM 1503 03.82 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
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EP 00 30 2476

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

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专利名称(译)	用于超声骨分析设备的校准和质量保证的设备和方法		
公开(公告)号	EP1038501A1	公开(公告)日	2000-09-27
申请号	EP2000302476	申请日	2000-03-27
[标]申请(专利权)人(译)	豪洛捷公司		
申请(专利权)人(译)	HOLOGIC INC.		
当前申请(专利权)人(译)	HOLOGIC INC.		
[标]发明人	WILSON KEVIN E BARRY DONALD LAMSER DENNIS G OBRIEN JOHN P STEIN JAY A		
发明人	WILSON, KEVIN E. BARRY, DONALD LAMSER, DENNIS G. O'BRIEN, JOHN P. STEIN JAY A.		
IPC分类号	A61B5/107 A61B8/08		
CPC分类号	A61B5/1074 A61B8/0875 A61B8/4209 A61B8/587		
优先权	09/277838 1999-03-26 US		
外部链接	Espacenet		

摘要(译)

一种校准具有一对换能器组件的超声骨分析设备的方法。每个换能器组件具有换能器和耦合垫，并且可相对于另一个移动，使得每个垫的面可以移动到它们在第一次压缩时相互接触的位置，并且移动到面接触身体部位的位置。在不同于第一次压缩的第二次压缩时。根据本申请的方法包括：当换能器组件处于第一位置和第二位置时，从一个换能器发送超声信号并且通过另一个换能器接收与发送的超声信号对应的信号。确定超声信号通过身体部位的时间，并确定基于换能器位置的身体部位的宽度。然后，使用时间和宽度值，计算通过带有挤压补偿的身体部位的超声信号的声速。

