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METHOD AND DEVICE FOR ESTIMATING AND CHARACTERISING BONE PROPERTIES

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Starting from this prior art the present invention relates to a process as disclosed in US-A-4,941,474 but providing parametric images, said process being characterized in that the ultrasound beam is obtained by using focused transducers and said beam is scanned along one or several directions different from the ultrasound propagation direction notably along orthogonal axes.

Claim

1. A method for the in vivo evaluation and characterization of the mechanical or architectural properties of bones, by propagation of an ultrasound wave through the bone and studying the interaction of this wave with the bone, in order to obtain parametric images comprising the steps of:

using at least one transducer emitting an ultrasound beam through the bone.

collecting the signals transmitted through the bone and/or reflected by the faces of the bone and/or scattered by the internal structures of the bone;

storing the signals thus obtained in a memory; and

processing the signals thus stored for measuring the propagation velocity of the ultrasound beam in the bone, the thickness of the bone, the transmission attenuation

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coefficient of the ultrasound beam and the reflection parameters for estimating the back-scatter and attenuation coefficients, characterized in that the ultrasound beam is obtained by using focused transducers and said beam is scanned along one or several directions different from the ultrasound propagation direction notably along orthogonal axes.

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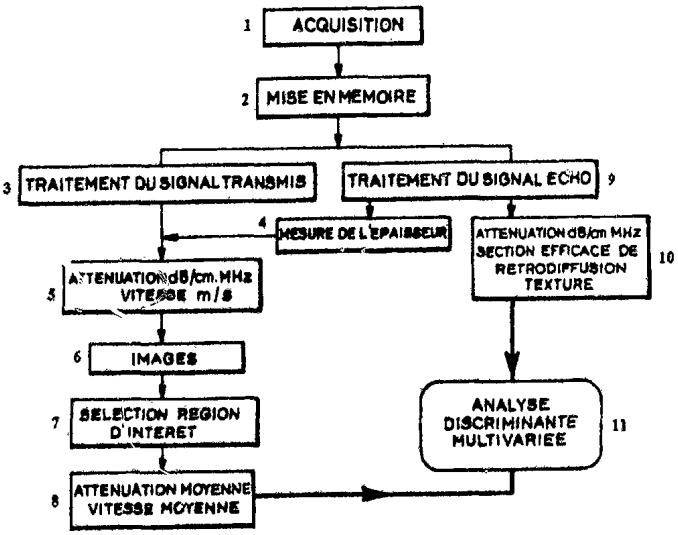
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(54) Title: METHOD AND DEVICE FOR ESTIMATING AND CHARACTERISING BONE PROPERTIES

(54) Titre: PROCEDE ET DISPOSITIF D'EVALUATION ET DE CARACTERISATION DES PROPRIETES DES OS

(57) Abstract

Method for *in vivo* estimation and characterisation of mechanical and structural bone properties, by propagating an ultrasonic wave through the bone and analysing the interaction between said wave and the bone, wherein the bone is scanned with an ultrasonic beam from focused transducers, signals transmitted through the bone and/or reflected by the bone surfaces and/or scattered by internal bone structures are collected, stored, and processed, to provide measurements for the propagation rate of the ultrasonic wave in the bone, bone thickness, the transmission attenuation coefficient of the ultrasonic beam, and the reflection parameters for the estimation of attenuation and backscatter coefficients.



(57) Abrégé

Procédé d'évaluation et de caractérisation *in vivo* des propriétés mécaniques ou architecturales des os, par propagation d'une onde ultrasonore au travers de l'os et l'étude de l'interaction de cette onde avec l'os, caractérisée en ce que: on réalise un balayage de l'os à l'aide d'un faisceau ultrasonore obtenu à partir de transducteurs focalisés; on recueille les signaux transmis au travers de l'os et/ou réfléchis par les faces de l'os et/ou diffusés par les structures internes de l'os; on met en mémoire les signaux obtenus et on traite les signaux ainsi stockés pour la mesure de la vitesse de propagation du faisceau ultrasonore dans l'os, de l'épaisseur de l'os, du coefficient d'atténuation en transmission du faisceau ultrasonore et des paramètres de réflexion pour l'estimation des coefficients de rétro-diffusion et d'atténuation.

Method and device for evaluating and characterizing the properties of bone

The present invention relates to a method for in vivo evaluation and characterization of the mechanical or architectural properties of bone, employing the ultrasound technique.

During the past few years, ultrasound equipment has appeared on the market which makes it possible to measure attenuation and its dependence as a function of frequency (attenuation coefficient), or the propagation velocity of ultrasound in transmission through the calcaneus or the patella. These devices are essentially intended for detecting or for monitoring osteoporosis.

A number of devices providing in vivo evaluation of bone by employing ultrasound beams are already known.

Publications WO 90/01903 and WO 87/07494 describe devices which make it possible to measure the propagation velocity of ultrasound in bone by using two transducers which are placed on either side of the bone.

Patent US 4,774,959 describes a device which measures the transmission attenuation coefficient using a first pair of transducers, this device including a second pair of transducers which measure the thickness of the bone where the ultrasound beam has passed through the bone.

European publications 0,341,969 and 0,480,554 describe devices which make it possible to measure the transmission attenuation coefficient and the velocity of ultrasound with the aid of a pair of transducers placed face to face.

Finally, Patent US 4,941,474 describes an apparatus which makes it possible to analyse both signals transmitted through the bone and signals which are reflected or scattered by the internal architecture of

the bone. Said apparatus comprises at least one transducer emitting an ultrasound beam through the bone, means for receiving and memorizing the signals which are transmitted through the bone or reflected by its surfaces and means for treating the stored signals in order to measure the propagation velocity of the ultrasound beam in the bone, its thickness, the transmission attenuation coefficient of the ultrasound beam and the scattering parameters. This apparatus cannot provide parametric images.

Experience derived from the use of the known apparatuses mentioned above shows that the measurements which can be carried out with them remain rudimentary, and that the accuracy, sensitivity and reproducibility of these measurements need to be improved. Furthermore none of this known devices can provide parametric images.

Starting from this prior art the present invention relates to a process as disclosed in US-A-4,941,474 but providing parametric images, said process being characterized in that the ultrasound beam is obtained by using focused transducers and said beam is scanned along one or several directions different from the ultrasound propagation direction notably along orthogonal axes.

In particular, the present invention provides a method for the in vivo evaluation and characterization of the mechanical or architectural properties of bones, by propagation of an ultrasound wave through the bone and studying the interaction of this wave with the bone, in order to obtain parametric images comprising the steps of:

using at least one transducer emitting an ultrasound beam through the bone.

collecting the signals transmitted through the bone and/or reflected by the faces of the bone and/or scattered by the internal structures of the bone;

storing the signals thus obtained in a memory; and

processing the signals thus stored for measuring the propagation velocity of the ultrasound beam in the bone, the thickness of the bone, the transmission attenuation coefficient of the ultrasound beam and the reflection parameters for estimating the back-scatter and attenuation coefficients, characterized in that the ultrasound beam is obtained by

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using focused transducers and said beam is scanned along one or several directions different from the ultrasound propagation direction notably along orthogonal axes.

According to a preferred form of the present invention, for producing, in transmission mode, parametric images of attenuation as a function of frequency and propagation of velocity of the ultrasound, use is made of a pair of focused transducers, placed opposite and operating at low frequency, that is to say at a central frequency of between 100 kHz and 3 MHZ, and preferably between 100 kHz and 1 MHZ.

In its application to producing reflectivity images in echographic mode (reflection mode), the preferred method of the present invention uses a

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focused transducer or a pair of focused transducers, placed opposite and capable of operating in a wider frequency range, that is to say at a central frequency of between 100 kHz and 10 MHz.

According to the preferred form of the present invention, for producing reflectivity images in echographic mode and for estimating the attenuation and/or back-scatter coefficients as a function of the frequency of the ultrasound beam, and also with a view to producing, in transmission, parametric images of attenuation as a function of frequency and of propagation velocity, use is made of a pair of transducers, placed opposite and operating at low frequency, that is to say at a central frequency of between 100 kHz and 3 MHz, preferably between 100 kHz and 1 MHz, and a focused transducer or a pair of focused transducers placed opposite and operating at high frequency, that is to say at a central frequency of between 1 MHz and 10 MHz.

The invention also relates to an apparatus making it possible to implement the method as specified hereinabove.

A device for implementing the method specified hereinabove includes means for emitting and receiving focused ultrasound, placed opposite on either side of the bone to be analysed, and is characterized in that it comprises: means making it possible to scan the ultrasound beam, an acquisition module including the means for emitting ultrasound and receiving the ultrasound signals after their interaction in the bone; a system for storing in memory the signals thus obtained, and a module for processing the said signals in order to estimate the acoustic parameters known for their relationship with the mechanical or viscoelastic properties of the bone.

According to one exemplary embodiment of the device forming the subject matter of the invention, use is made of focused transducers, placed opposite, these transducers being of the single-element type.

According to another embodiment of the present invention the measurements may be carried out in immer-

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sion, the device then including an enclosure filled with a liquid such as water, or else these measurements can be carried out by contact with the aid of a coupling medium and by using an array of ultrasound transducers.

This preferred device is furthermore characterized in that the module for processing the signal includes a computer, a bulk memory and a signal-processing software package designed to analyse the data originating from the acquisition module, this processing module including a set of functions making it possible, in particular, to calculate the transmission attenuation coefficient, calculate the thickness of bone passed through at the location of the measurement, calculate the propagation velocity, calculate the reflection back-scatter coefficient and calculate the reflection attenuation coefficient.

Other characteristics and advantages of the present invention will emerge from the description given hereafter with reference to the attached drawings, which illustrate various examples of implementation and embodiments thereof, without any limiting character.

In the drawings:

- Figure 1 is a schematic view in elevation, representing one exemplary embodiment of an apparatus for implementing the method forming the subject matter of the invention;
- Figure 2 is a block diagram illustrating overall the data acquisition module employed by the invention;
- Figure 3 is also a diagram illustrating overall an acquisition module operating simultaneously in transmission and in reflection;
- Figure 4 is a diagram illustrating the principle of acquisition in transmission;
- Figure 5 is a diagram which illustrates the general principle of acquisition in transmission and in reflection;
- Figure 6 is a diagram illustrating a variant of the acquisition mode in transmission and reflection;
- Figure 7 is a block diagram illustrating the general principle of the signal processing and the method and the device forming the subject matter of the invention;

AUSTRALIAN PATENT OFFICE

- Figure 8 is a diagram illustrating the processing of the transmitted signal with a view to measuring the propagation velocity of the ultrasound wave in bone;
- Figure 9 is another diagram illustrating the processing of the signal, in echographic mode, with a view to measuring the thickness of bone, and
- Figure 10 is a block diagram illustrating the principle of the processing of the transmitted signal for measuring attenuation.

Referring to Figure 1, it is seen that, in this nonlimiting exemplary embodiment, the device implementing the method forming the subject matter of the invention essentially includes an enclosure 10 filled with water, making it possible to take the measurements during immersion, the presence of the liquid medium ensuring good coupling between the radiation source and the bone, of which it is desired to evaluate, in particular, the mechanical properties. This device includes an ultrasound emission source, here consisting of pairs of focused piezoelectric ultrasound transducers, placed opposite on either side of the bone to be analysed, one of the pairs of transducers such as 12 operating at high frequency, that is to say in the frequency range of from 1 MHz to 10 MHz, specified hereinabove, whereas the pair of transducers such as 14, operate at low frequency in a range of between 100 kHz and 1 MHz. These pairs of transducers are mounted on a mobile bridge which, in Figure 1, has been represented respectively in the raised position 16 and in the position 16′ lowered for measurement.

As specified hereinabove, the principle on which the method forming the subject of the invention is based resides in transmitting an ultrasound wave into the bone and in studying the interaction of this wave with the bone. The device according to the invention, illustrated by Figure 1, can operate both in transmission and in reflection. In this exemplary embodiment, it is equipped with a conventional system for scanning the ultrasound beam, this scanning being obtained by displacement of the

focused transducers under the action of two motors which displace them in a plane, along the orthogonal axes X and Y, thus allowing the entire bone volume to be explored.

The device furthermore includes an acquisition module tasked with emitting the ultrasound signals and receiving these signals after they have interacted in the bone. A system for storing in memory the signals thus obtained is also provided, as is a module for processing these signals in order to estimate certain acoustic parameters known for their relationship with the mechanical or viscoelastic properties of the bone.

The invention, in particular by virtue of automatic scanning of the ultrasound beam, provides a solution to the difficulties resulting from the use of current apparatuses, in particular as regards accurate positioning of the bone for measurement and location of the region in which the measurement takes place. The invention furthermore makes it possible to carry out ultrasound measurements in transmission through the bone and in reflection. Collection of the signals reflected and/or scattered by the internal architecture of the bone provides information complementary to that already contained in the signals which have been transmitted through the bone. The device according to the invention thus makes it possible to obtain substantially more information than is obtained by devices of known types. The invention furthermore provides better precision.

As specified in the preamble of the present description, the method forming the subject matter of the invention makes it possible to obtain, in transmission mode, parametric images of attenuation as a function of frequency and of propagation velocity of the ultrasound beam, by employing a pair of focused transducers, placed opposite and operating at low frequency, that is to say at a central frequency between 100 kHz and 1 MHz.

The invention also makes it possible to produce reflectivity images in echographic mode and to obtain an estimate of the attenuation and back-scatter coefficients, by using a single focused transducer or a pair of

focused transducers, placed opposite and operating at high frequency, that is to say at a central frequency of between 1 MHz and 10 MHz.

Finally, it is also possible, by virtue of the method of the invention, to produce reflectivity images in echographic mode and obtain an average estimate of the attenuation and/or back-scatter coefficients as a function of the frequency of the ultrasound beam, and also to produce in transmission parametric images of attenuation as a function of frequency and of propagation velocity of the ultrasound beam. In this application, the invention employs a pair of transducers, placed opposite and operating at low frequency, that is to say at a central frequency of between 100 kHz and 1 MHz, and a pair of focused transducers, placed opposite and operating at high frequency, that is to say at a central frequency of between 1 MHz and 10 MHz.

As already specified hereinabove, the device implementing the method according to the invention essentially includes an "ultrasound signal acquisition" module and a "signal processing" module.

The "acquisition" module has the functions:
- of emitting the ultrasound waves with the aid of the transducers defined hereinabove;
- of receiving the so-called reference ultrasound waves, receiving ultrasound waves transmitted through the bone, and receiving waves reflected and/or scattered by the bone and its structures;
- scanning the entire bone volume with the ultrasound beam.

This "acquisition" module is composed, as defined hereinabove, of ultrasound sources and receivers (pair of focused transducers). The ultrasound pulse thus radiated is transmitted into the propagation medium, with which it interacts. As has been specified hereinabove, the measurement can be carried out in immersion in order to obtain good coupling between the radiation source and the bone. The interaction between the propagation medium and the incident wave gives rise to a directly transmitted

wave (coherent wave) and one or more waves reflected or scattered by the bone and/or its internal structures.

This "acquisition" module is furthermore composed of a stage for detection, amplification (for example automatic gain control) and analogue-digital conversion of the signals, of a computer, and of a processor with its conventional environment. This part of the device is of conventional design and will consequently not be described.

This module furthermore includes, in this exemplary embodiment, the mechanical device which scans the ultrasound beam in a plane perpendicular to the direction of propagation of the ultrasound beams. During scanning, the ultrasound emitter and receiver execute the same movement synchronously, so that their relative position remains identical. This scanning is produced with the aid of two programmable motors.

Figure 2 is an overall diagram of the device according to the invention, providing operation only in transmission mode. This device includes a transducer T1 for emission, associated with a transducer T'1 for reception and arranged opposite. The transducers are focused, the distance separating them being approximately equal to twice the focal length. The transducer T'1 detects the waves emitted by the transducer T1 and converts them into an electrical signal which is amplified, digitized and transferr d to the computer.

Figure 3 represents an overall diagram of a device operating both in transmission and reflection mode. An ultrasound transducer T2 or T3 is periodically excited such as to radiate an ultrasound wave into the propagation medium. This wave interacts with the propagation medium and it undergoes partial reflection and/or scattering. A part of the incident energy is reflected on entering the bone, a part of the energy transmitted into the bone is subsequently scattered by the internal structures of the latter, and in particular back-scattered to the emitter transducer T2 or T3. It is this same transducer (T2 or T3) which is used as a receiver for

detecting the waves reflected by the bone and back-scattered by the internal architecture of the latter, and for converting them into an electrical signal which is subsequently amplified, digitized and transferred to the computer. The transducer T2 or T3 is electrically connected to the reception stage. The combined use in reflection of two transducers T2 and T3, placed opposite, makes it possible simultaneously to detect the echoes from two opposite faces of the bone. An automatic ultrasonic measurement of the thickness of the bone can thus be carried out. In addition, signal processing can be carried out subsequently on the back-scattered signals recorded by the transducers T2 or T3, in order to extract the acoustic parameters useful for characterizing the bone: attenuation as a function of frequency, back-scatter cross-section, texture parameter, etc.

In order to operate simultaneously in transmission and in reflection with two pairs of transducers placed opposite, use is preferably made of the solution illustrated by Figure 3, according to which three pulse-generator stages are used to control the transducers T1, T2 and T3, the excitations being sequential in time: T1 emits first, when T'1 has detected the wave emitted by T1, T2 emits and it detects the reflected and back-scattered signals. Finally, T3 is excited in turn.

Another more economical but less fast solution consists in using only a single common pulse generator for exciting the transducers T1, T2 and T3. In this case, it is sufficient to provide a switch in order to direct the excitation pulse to a different transducer at each shot. This switch is connected to the microprocessor which controls the switching. This variant has not been represented.

Figure 4 represents the transmission acquisition diagram. The various steps in this acquisition are clearly seen on examining the figure.

Two solutions may be used for acquiring data in transmission and in reflection.

In the first solution, illustrated by Figure 5,

the transmitted and reflected data are recorded during a single scan. For each position X, Y, transducers T1, T2, T3 are excited successively. In the second solution, illustrated by Figure 6, the transmitted and reflected data are recorded during three different scans: the first scan is intended for acquisition of data by the pair of transducers T1 and T'1, and the second and third scans are intended of acquisition of data in reflection by the transducers T2 and T3.

It is possible to acquire a plurality of signals one after the other for a fixed position of the transducers. The signal/noise ratio is improved by means of these various acquisitions. In the event that this possibility exists, emission/reception is repeated as many times as is necessary. Once this acquisition sequence is completed, the position of the motors is incremented and the operation can be repeated.

As soon as the signal acquisition phase has been completed, all the digitized signals are stored in memory and the signal processing phase can then commence, either automatically or by means of a command initiated by the operator.

As has been specified hereinabove, the device implementing the present invention includes a signal processing module. The general principle of the signal processing is illustrated by the diagram in Figure 7.

This signal processing module includes a computer, a bulk memory and a signal processing software package designed for analysing the data previously acquired in transmission and/or in reflection. It includes a set of preprogrammed functions making it possible, in particular, to perform the following calculations:

- calculation of the attenuation (in dB) as a function of frequency in transmission
- calculation of the attenuation coefficient as a function (in dB/MHz) of frequency in transmission
- calculation of the times of flight of the signals transmitted through the bone

- calculation of the bone thickness passed through at the measurement location
- calculation of the attenuation coefficient as a function of frequency (dB/cm.MHz) in transmission
- calculation of the propagation velocity of the ultrasound in transmission
- calculation of the attenuation (in dB) as a function of frequency in reflection
- calculation of the attenuation coefficient as a function of frequency (dB/cm.MHz) in reflection
- calculation of the back-scatter cross-section (in dB) as a function of frequency in reflection
- calculation of the back-scatter coefficient (dB/MHz) in reflection
- calculation of the integral back-scatter coefficient (dB.MHz) in reflection.

It is, of course, possible to add other signal-processing or image-processing functions which can provide quantitative information that is useful for characterizing the bone (texture analysis, for example).

The parameters are obtained for each position of the transducers, which makes it possible to obtain a parameter map. Image processing is included in the software, thus making it possible to select one or more regions of the measurement, having arbitrary shape, for estimation of a local mean of these parameters.

The method of estimating the parameters (attenuation and propagation velocity) in transmission relies on comparison of a reference signal with a signal transmitted through the bone.

The reference signal is a signal which has propagated through a medium, the acoustic characteristics (attenuation and velocity) of which are well known (water, in this exemplary embodiment). The reference signal and the signals transmitted through the bone are recorded under the same conditions. For example, the reference signal may be acquired either when starting the apparatus, or before each examination. It is also possible to record a single reference and store it in the

memory of the computer in order to recall it subsequently on each examination.

A description will now be given by way of example of various signal processing modes for certain functions carried out by the method of the invention.

1. Estimation of the propagation velocity in transmission.

The principle of processing the transmitted signal in order to measure this velocity is illustrated by the diagram in Figure 8. This processing mode therefore includes the following steps:

- the transducers are at the position X, Y;

The transducer T1 emits and the wave thus emitted, transmitted through the bone, is detected by the receiver transducer T'1, then amplified, digitized and transferred to the computer. Of course, and as specified hereinabove, for measurements through the calcaneus, the transducers and the bone are placed in a bath, the temperature of which is controlled by a thermostat (see Figure 1). This first measurement is intended for estimating the time of flight of the wave transmitted through the bone and for calculating the difference between this time of flight and that of the reference signal;

- the transducer T2 (or T1) emits and the transducer T2 (or T1) receives the signal thus emitted and reflected by the bone. The reflected ultrasound wave is amplified, digitized and transferred to the computer.

- the duration of the time of flight of the echo which is reflected by the entry face of the bone, facing the transducer T2 (or T1), is estimated;

- the transducer T3 (or T'1) emits and the transducer T3 (or T'1) receives the signal reflected by the bone. The reflected wave is amplified, digitized and transferred to the computer;

- the duration of the time of flight of the echo reflected by the entry face of the bone, which is turned towards T3 (or T'1), is estimated;

- these latter two measurements are intended for calculating the thickness of the calcaneus at the location of

the measurement. The propagation velocity in transmission of the ultrasound wave is deduced in a known manner from the time of flight of the wave between the two transducers. In order to estimate the propagation velocity, it is necessary to know the thickness of the bone and this, according to the invention, is measured by ultrasound.

Figure 9 illustrates the principle of processing the principle of processing the echographic signal in order to measure this thickness. In fact, using echography, it is possible to determine the distance separating a transducer from the face of the bone, (face of interest). It is sufficient to identify the echo from this face and to measure its time of flight. Each transducer T2 and T3 (or T1 and T'1) is interrogated in turn in echographic mode, and the times of flight T1 and T2 of the echoes reflected by each of the opposite lateral faces of the bone are measured. The thickness of the bone is deduced therefrom.

2. Estimation of the attenuation coefficient in transmission.

The principle of the signal processing according to this particular mode is illustrated by Figure 10. It includes the following steps:

- the transducers are initially in the position X, Y;
- the transducer T1 emits and the wave transmitted through the bone is detected by the receiver transducer T'1, then it is amplified, digitized and transferred to the computer. As before, for measurements through the calcaneus, in this embodiment, the transducers and the bone are placed in a bath, the temperature of which is controlled by a thermostat (Figure 1);
- the frequency spectra of the signal transmitted through the bone and of the reference signal are calculated. The attenuation as a function of frequency is obtained by comparing the spectrum of a reference signal recorded in water with that of the signal transmitted through the bone. The ultrasound signal is of the pulse type and it includes a plurality of frequencies in the interval between 0.2 MHz and 1 MHz.

In order to overcome variations connected with the thickness of the calcaneus, it is necessary to compare the attenuations normalized to the exact thickness (dB/MHz.cm) of the calcaneus at the measurement point. The manner according to which an ultrasonic thickness measurement can be carried out in echographic mode was explained hereinabove.

As in the case of all heterogeneous media, the value of the acoustic parameters depends on the location where the measurement is taken. The scanning device of the apparatus according to the invention makes it possible to explore the entire bone volume and to obtain a parameter map. On the basis of the images of attenuation as a function of frequency and of velocity of the ultrasound wave, it is possible to select a measurement region (region of interest) and to estimate a mean of the parameters in this region. The software comprises some simple image-processing functions, in particular for selecting measurement regions of variable shape and size. The support of the image is used for selecting identical measurement regions in different patients or during repeated measurements in a single patient.

The invention thus makes it possible to obtain, in particular, ultrasound imaging of the calcaneus (attenuation and velocity images) by virtue of using focused transducers, the images thus obtained being comparable with those obtained by a scanner.

3. Estimation of the attenuation coefficient and of the back-scatter cross-section in reflection, as a function of frequency.

The various steps in this mode of processing the transmitted signals are the following:

- the transducers are at the position X and Y;
- the transducer T2 (or T3, or T1, or T'1) emits;
- the transducer T2 (or T3, or T1, or T'1) receives the echographic signal back-scattered by the internal architecture of the bone, this signal being subsequently amplified, digitized and transferred to the computer.
- a sliding spectral analysis of the echographic signal

is carried out, and the spectra are estimated as a function of depth;

- the spectral centroids are calculated as a function of depth;
- the attenuation coefficient is calculated as a function of frequency (dB/cm.MHz) in reflection;
- the spectral difference between the spectrum of the signal and a reference spectrum is calculated, then the back-scatter cross-section (in dB) is calculated as a function of frequency in reflection;
- the back-scatter coefficient (dB/MHz) in reflection is calculated; and
- the integral back-scatter coefficient (dB.MHz) in reflection is calculated. Scanning the ultrasound beam makes it possible to explore the entire bone volume. The attenuation and back-scatter coefficients are calculated for each position of the transducers. It is then possible to estimate a local average of the parameters within a region of interest selected by the operator.

The attenuation can be estimated on the basis of the sampled radio-frequency echographic signal. The principle of calculating the attenuation relies on time/frequency analysis of the echographic signal.

The invention thus makes it possible to measure the back-scatter cross-section as a function of frequency. It is known that the physical properties of bone tissue are indeed demonstrated by this measurement.

It results from reading the above description that the invention provides a solution to the difficulties posed by employing bone-analysis ultrasound apparatuses currently on the market:

- the device for automatically scanning the ultrasound beam makes it possible to solve the problem of accurate positioning of the bone and of positioning of the measurement region or region of interest;
- the use of focused transducers makes it possible to obtain high-quality images;
- it makes it possible to obtain ultrasound measurements in transmission through the bone and in reflection;

- it makes it possible to collect and process signals reflected and/or scattered by the internal architecture of the bone, which provides information in addition to that already found in the signals which have been transmitted through the bone. The method and the device forming the subject matter of the invention thus provide much more information than is provided with devices according to the prior art, while offering better accuracy, reproducibility and sensitivity.

Among the fields of application of the invention, osteoporosis was specified hereinabove. In this application, the invention provides a non-traumatic physical method for in vivo evaluation of the bone quality (mass, rigidity, architecture). The risk of fracture associated with a decrease in the strength of the bones can thus be assessed quantitatively, this decrease being, as is known, a consequence of the phenomena of the demineralization and bone architecture modification encountered in osteoporosis.

The description given hereinabove of exemplary embodiments of the invention is not limited to measurements of the calcaneus and of the patella: there are, of course, other fields of application of the invention, particularly with a view to monitoring the degree of mineralization of the skeleton, in particular in order to follow the evolution of the bone architecture or of the elasticity of the bone structure. Among these applications, mention may be made, in particular, of:

- skeletal maturation in neonates;
- secondary osteoporosis, osteomalacia, etc.;
- monitoring of racehorses;
- in vitro characterization of bone parts.

It remains clear that the present invention is not limited to the modes of implementation nor to the exemplary embodiments described and/or represented here, but that it encompasses all variants thereof. Thus, the exemplary embodiment described here refers to measurements carried out in immersion. However, without departing from the scope of the present invention, the

measurements may be carried out by contact, using an array of transducers and a coupling medium, it being possible to scan the ultrasound beam electronically.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for the in vivo evaluation and characterization of the mechanical or architectural properties of bones, by propagation of an ultrasound wave through the bone and studying the interaction of this wave with the bone, in order to obtain parametric images comprising the steps of:

using at least one transducer emitting an ultrasound beam through the bone.

collecting the signals transmitted through the bone and/or reflected by the faces of the bone and/or scattered by the internal structures of the bone;

storing the signals thus obtained in a memory; and

processing the signals thus stored for measuring the propagation velocity of the ultrasound beam in the bone, the thickness of the bone, the transmission attenuation coefficient of the ultrasound beam and the reflection parameters for estimating the back-scatter and attenuation coefficients, characterized in that the ultrasound beam is obtained by using focused transducers and said beam is scanned along one or several directions different from the ultrasound propagation direction notably along orthogonal axes.

2. A method according to Claim 1 for producing, in transmission mode, parametric images of attenuation as a function of frequency and propagation of velocity of the ultrasound beam, characterized in that is made of a pair of focused transducers, placed opposite and operating at central frequency of between 100 kHz and 3 MHZ, and preferably between 100 kHz and 1 MHZ.

3. A method according to Claim 1 for producing reflectivity images in echographic mode, characterized in that it uses a focused transducer or a pair of focused transducers, placed opposite and capable of operating at a central frequency of between 100 kHz and 10 MHZ.

4. A method according to Claim 1, applied to producing reflectivity images in echographic mode and to estimating the attenuation and/or back-scatter coefficients as a

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function of the frequency of the ultrasound beam, and also with a view to producing, in transmission, parametric images of attenuation as a function of frequency and of propagation velocity, characterized in that use is made of a pair of transducers, placed opposite and operating at a central frequency of between 100 kHz and 1 MHZ, and a focused transducer or a pair of focused transducers placed opposite and operating at a central frequency of between 1 MHZ and 10 MHZ.

5. A device for implementing the method according to any one of the preceding claims, including means for emitting and receiving focused ultrasound, placed opposite on either side of the bone to be analysed, an acquisition module including the means for emitting ultrasound and receiving the ultrasound signals after their interaction in the bone; a system for storing in memory the signals thus obtained, and a module for processing the said signals in order to estimate the acoustic parameters known for their relationship with the mechanical or viscoelastic properties of the bone characterized in that said means for emitting and receiving ultrasound signals are of the focused type and that it includes means for scanning the ultrasound beam thus obtained.

6. A device according to Claim 5, characterized in that the module for processing the signal includes a computer, a bulk memory and a signal-processing software package designed to analyse the data originating from the acquisition module, this processing module including a set of functions making it possible, in particular, to calculate the transmission attenuation coefficient, calculate the thickness of bone passed through at the location of the measurement, calculate the propagation velocity, calculate the reflection back-scatter coefficient and calculate the reflection attenuation coefficient.

7. A device according to either of Claims 5 or 6, characterized in that it includes focused transducers of the single-element type placed opposite.

8. A device according to any one of Claims 5 to 7, characterized in that it includes an enclosure filled with a liquid such as water, in order to take measurement during immersion.

AUSTRALIAN PATENT OFFICE

9. A device according to any one of Claims 5 to 7, characterized in that the measurements are carried out by contact with the aid of a coupling medium.

10. A device according to any one of claims 5 to 9, characterized in that use is made of an array of ultrasound transducers, scanning of which can be carried out electronically.

11. A method for the in vivo evaluation and characterization of the mechanical or architectural properties of bones, by propagation of an ultrasound wave through the bone and studying the interaction of this wave with the bone, in order to obtain parametric images substantially as hereinbefore described with reference to the accompanying drawings.

12. A device for implementing the method of Claim 1, substantially as hereinbefore described with reference to the accompanying drawings.

DATED this 22nd day of January, 1998

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
By its Patent Attorneys
Davies Collison Cave

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ABSTRACT

Method for the in vivo evaluation and characterization of the mechanical or architectural properties of bones, by propagation of an ultrasound wave through the bone and studying the interaction of this wave with the bone, characterized in that:

- the bone is scanned using an ultrasound beam obtained from focused transducers;
- the signals transmitted through the bone and/or reflected by the faces of the bone and/or scattered by the internal structures of the bone are collected;
- the signals obtained are stored in memory, and
- the signals thus stored are processed for measuring the propagation velocity of the ultrasound beam in the bone, the thickness of the bone, the transmission attenuation coefficient of the ultrasound beam and the reflection parameters for estimating the back-scatter and attenuation coefficients.

(Figure 7)

FIG. 1

21126.1'15

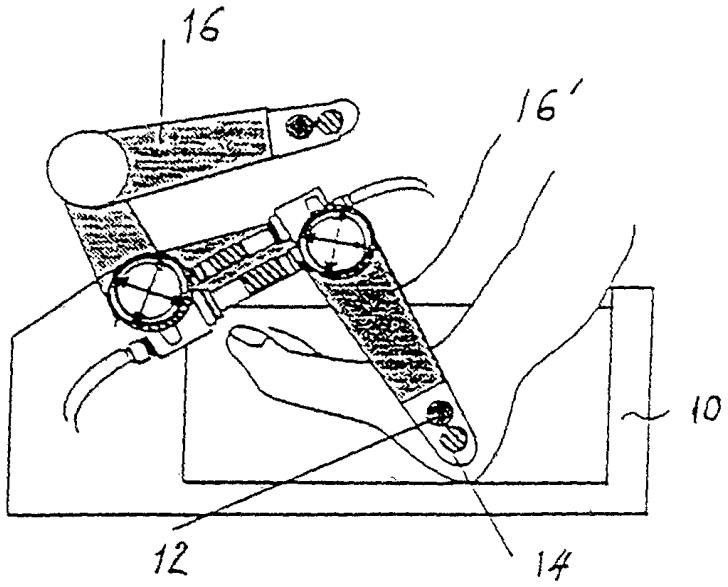


FIG. 7

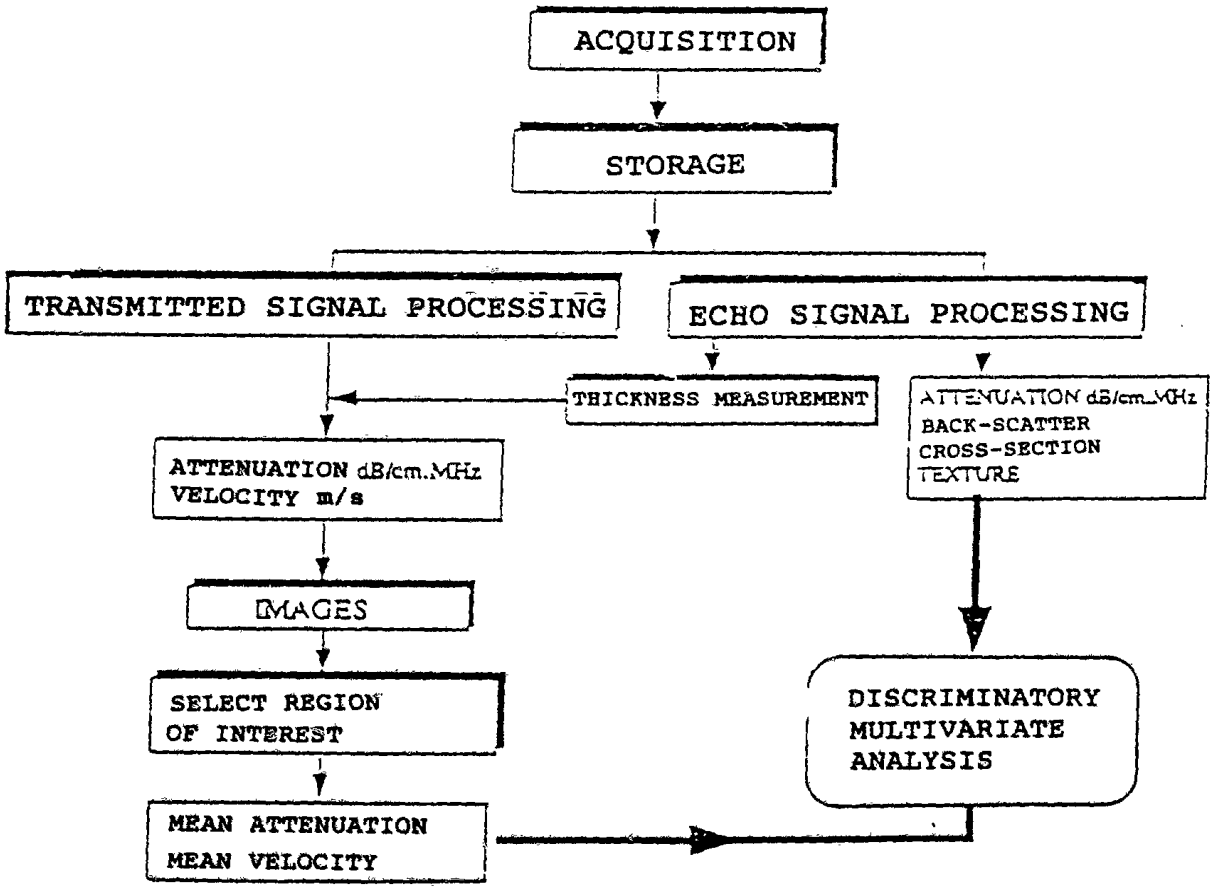


FIG 2

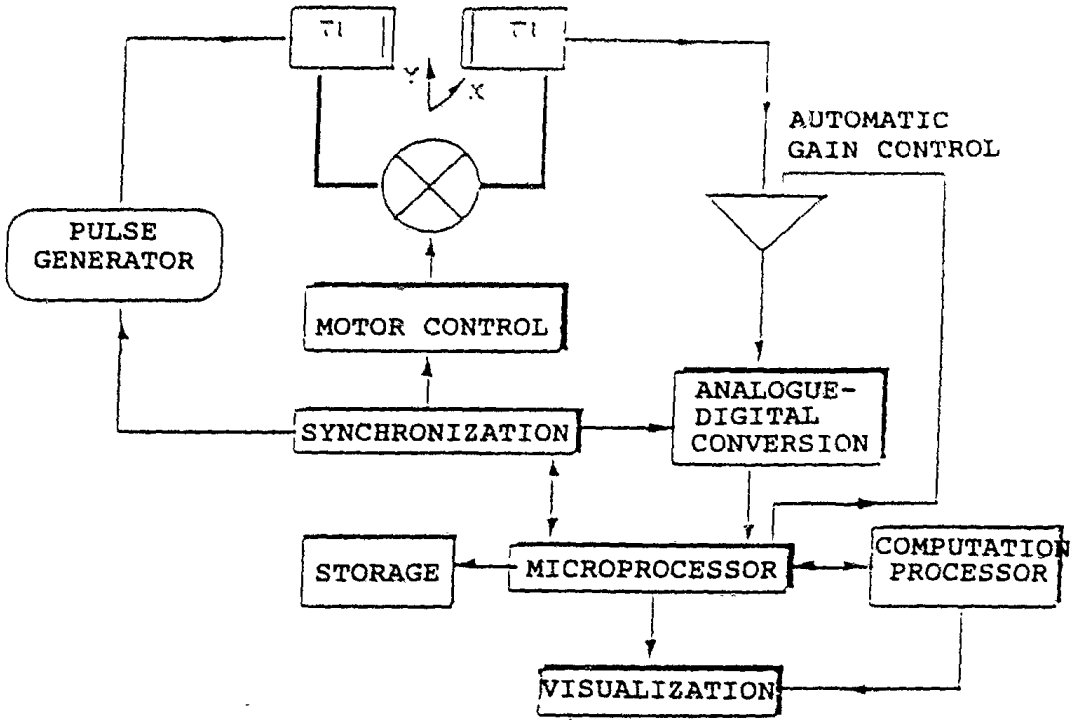

T1
T1
Y
X
AUTOMATIC
GAIN CONTROL
PULSE
GENERATOR
MOTOR CONTROL
SYNCHRONIZATION
ANALOGUE-
DIGITAL
CONVERSION
STORAGE
MICROPROCESSOR
COMPUTATION
PROCESSOR
VISUALIZATION

FIG. 3

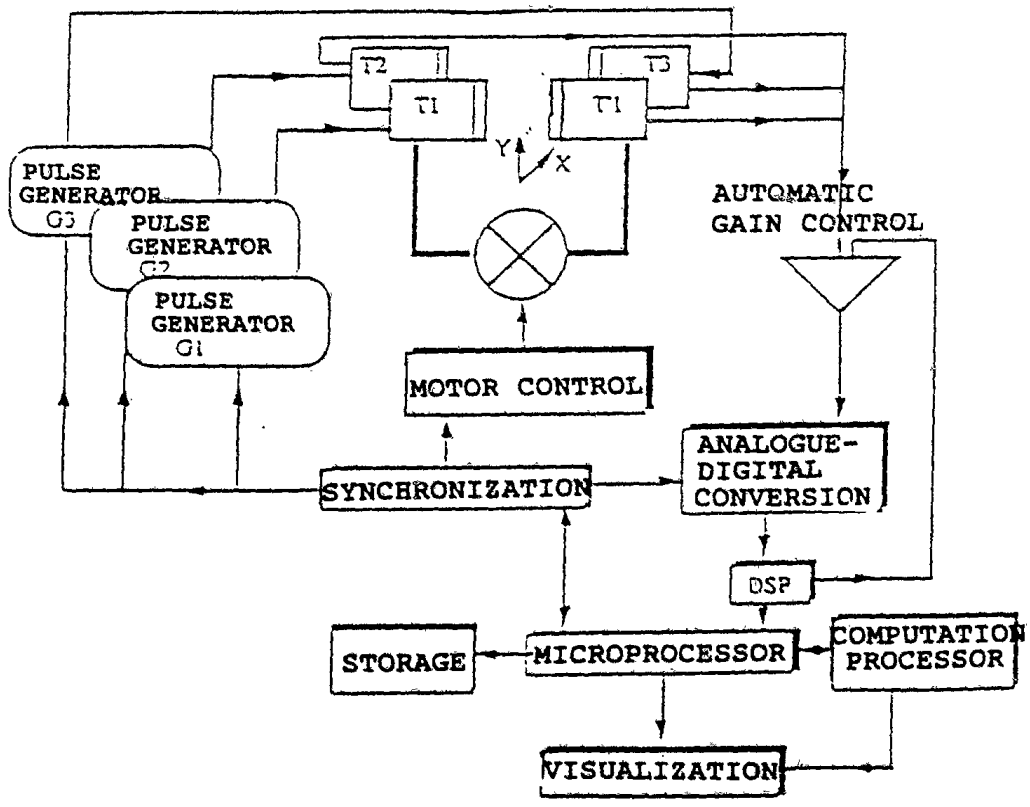

T2
T3
T1
T1
Y
X
PULSE
GENERATOR
G3
PULSE
GENERATOR
G2
PULSE
GENERATOR
G1
AUTOMATIC
GAIN CONTROL
MOTOR CONTROL
SYNCHRONIZATION
ANALOGUE-
DIGITAL
CONVERSION
DSP
STORAGE
MICROPROCESSOR
COMPUTATION
PROCESSOR
VISUALIZATION

FIG. 4

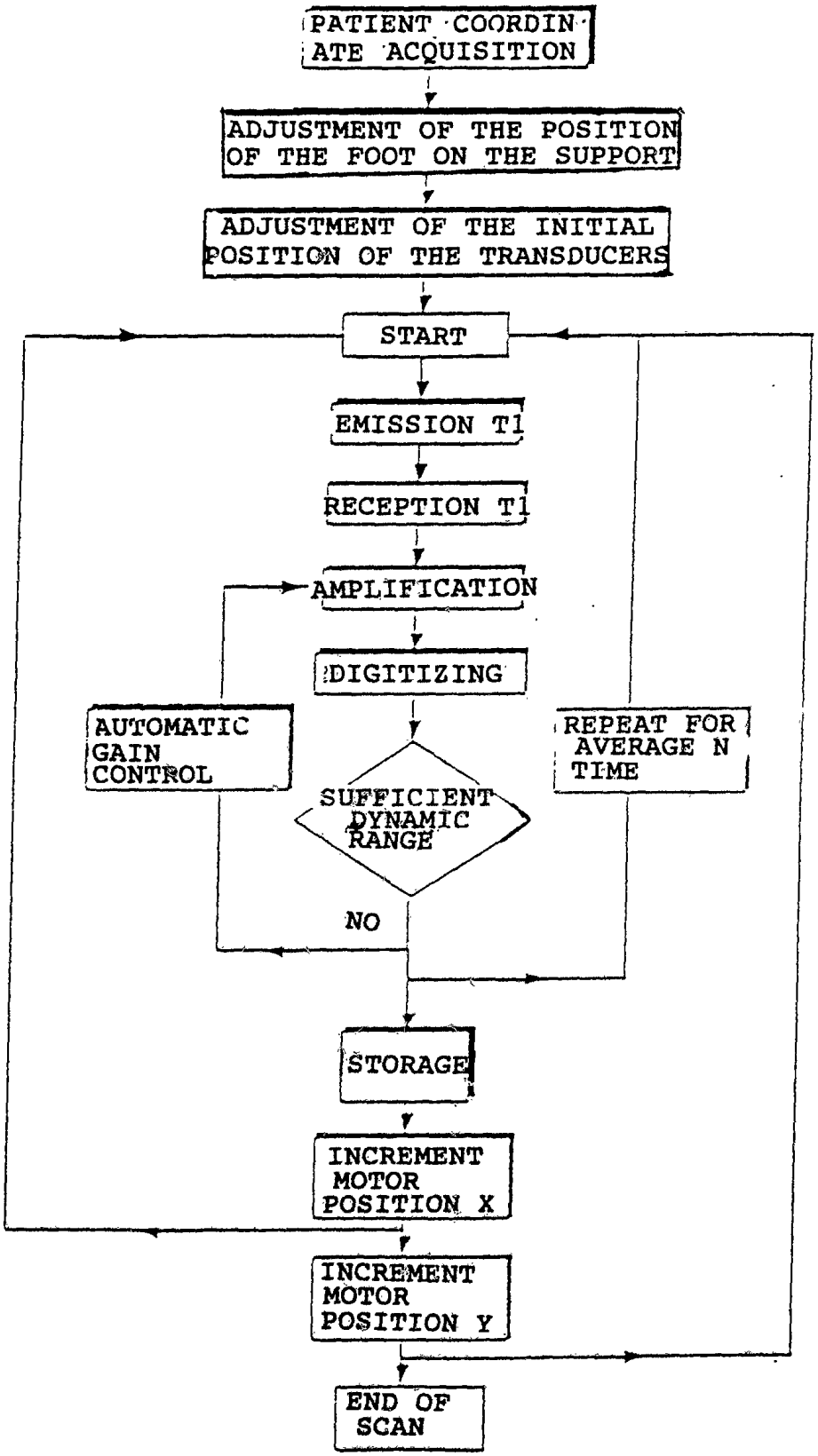
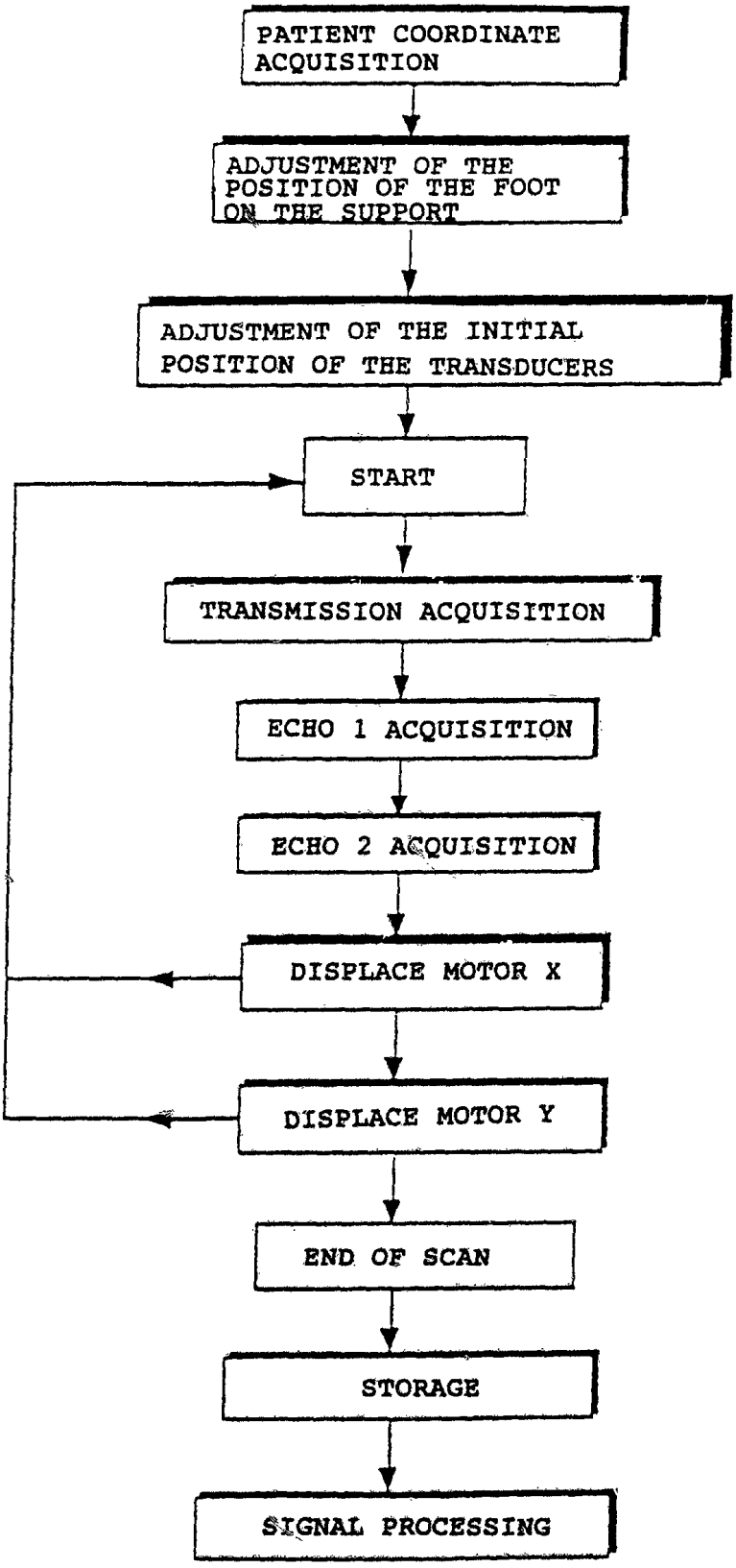

PATIENT COORDINATE ACQUISITION
ADJUSTMENT OF THE POSITION OF THE FOOT ON THE SUPPORT
ADJUSTMENT OF THE INITIAL POSITION OF THE TRANSDUCERS
START
EMISSION T1
RECEPTION T1
AMPLIFICATION
DIGITIZING
AUTOMATIC GAIN CONTROL
SUFFICIENT DYNAMIC RANGE
REPEAT FOR AVERAGE N TIME
NO
STORAGE
INCREMENT MOTOR POSITION X
INCREMENT MOTOR POSITION Y
END OF SCAN

FIG. 5


PATIENT COORDINATE ACQUISITION
ADJUSTMENT OF THE POSITION OF THE FOOT ON THE SUPPORT
ADJUSTMENT OF THE INITIAL POSITION OF THE TRANSDUCERS
START
TRANSMISSION ACQUISITION
ECHO 1 ACQUISITION
ECHO 2 ACQUISITION
DISPLACE MOTOR X
DISPLACE MOTOR Y
END OF SCAN
STORAGE
SIGNAL PROCESSING

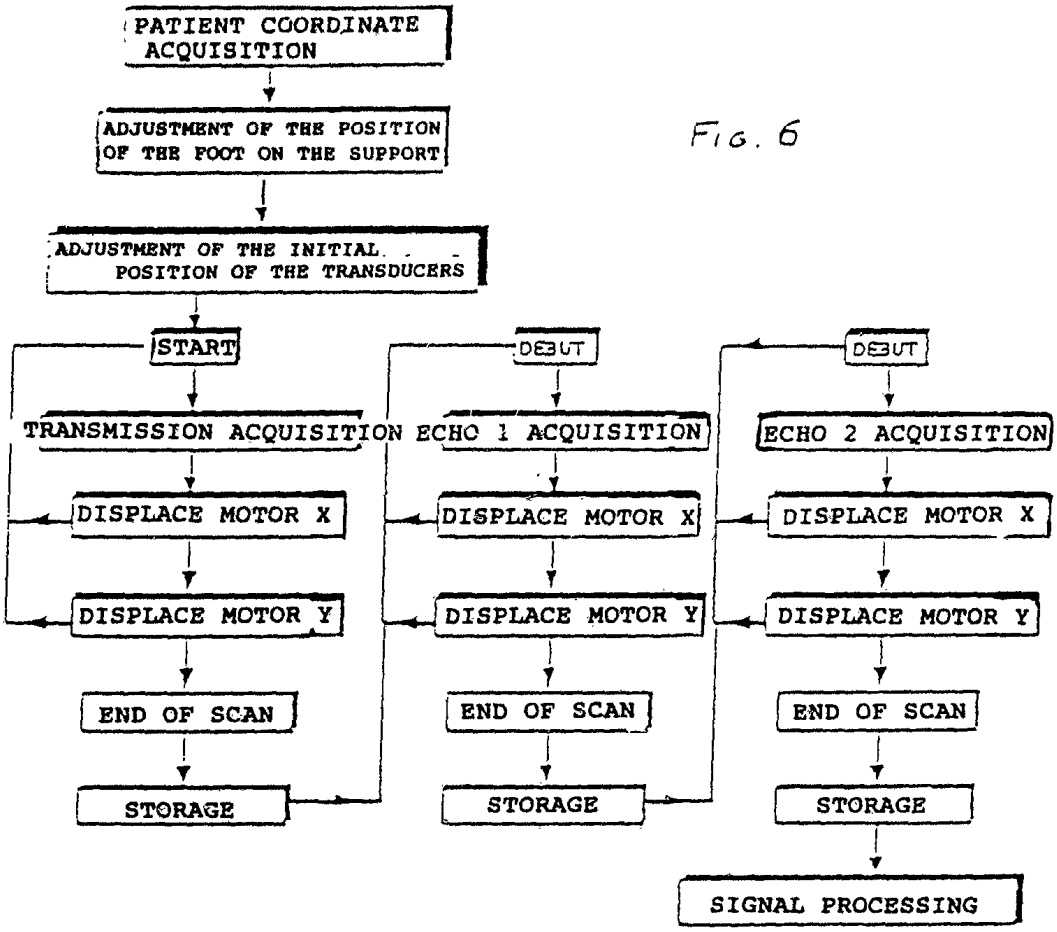

PATIENT COORDINATE ACQUISITION
ADJUSTMENT OF THE POSITION OF THE FOOT ON THE SUPPORT
ADJUSTMENT OF THE INITIAL POSITION OF THE TRANSDUCERS
START
TRANSMISSION ACQUISITION
DISPLACE MOTOR X
DISPLACE MOTOR Y
END OF SCAN
STORAGE
DEBUT
ECHO 1 ACQUISITION
DISPLACE MOTOR X
DISPLACE MOTOR Y
END OF SCAN
STORAGE
DEBUT
ECHO 2 ACQUISITION
DISPLACE MOTOR X
DISPLACE MOTOR Y
END OF SCAN
STORAGE
SIGNAL PROCESSING

Fig. 6

Fig. 9

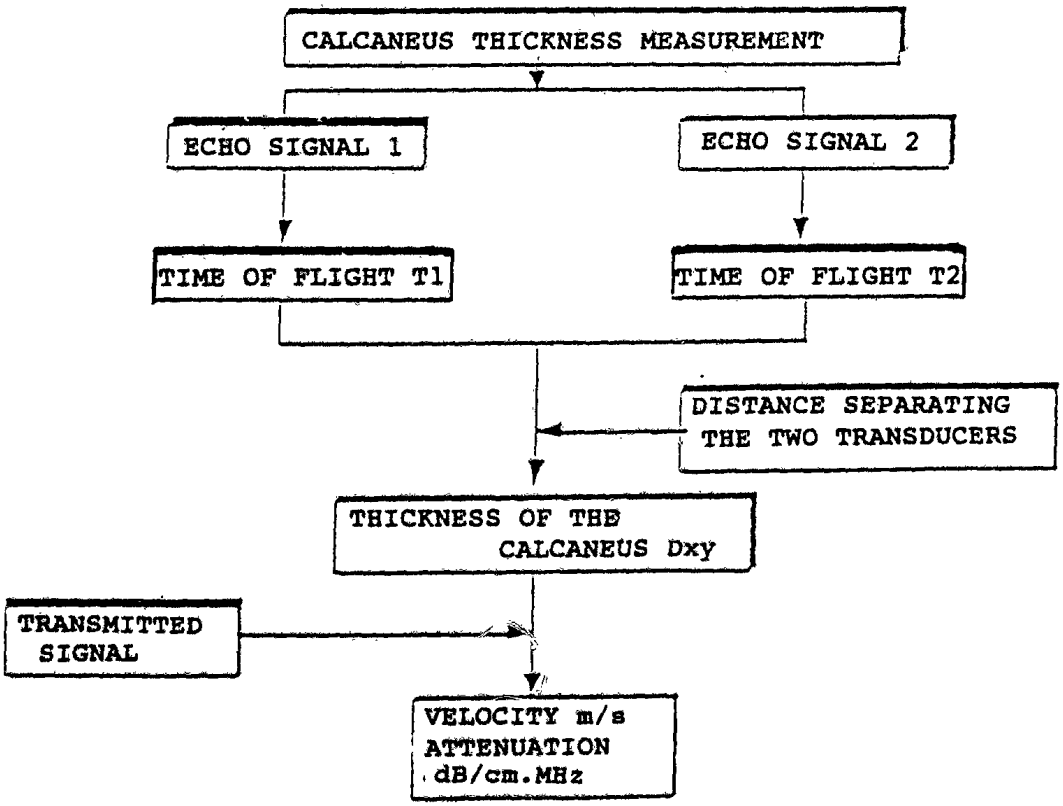

CALCANEUS THICKNESS MEASUREMENT
ECHO SIGNAL 1
ECHO SIGNAL 2
TIME OF FLIGHT T1
TIME OF FLIGHT T2
DISTANCE SEPARATING THE TWO TRANSDUCERS
THICKNESS OF THE CALCANEUS Dxy
TRANSMITTED SIGNAL
VELOCITY m/s
ATTENUATION dB/cm.MHz

FIG. 8

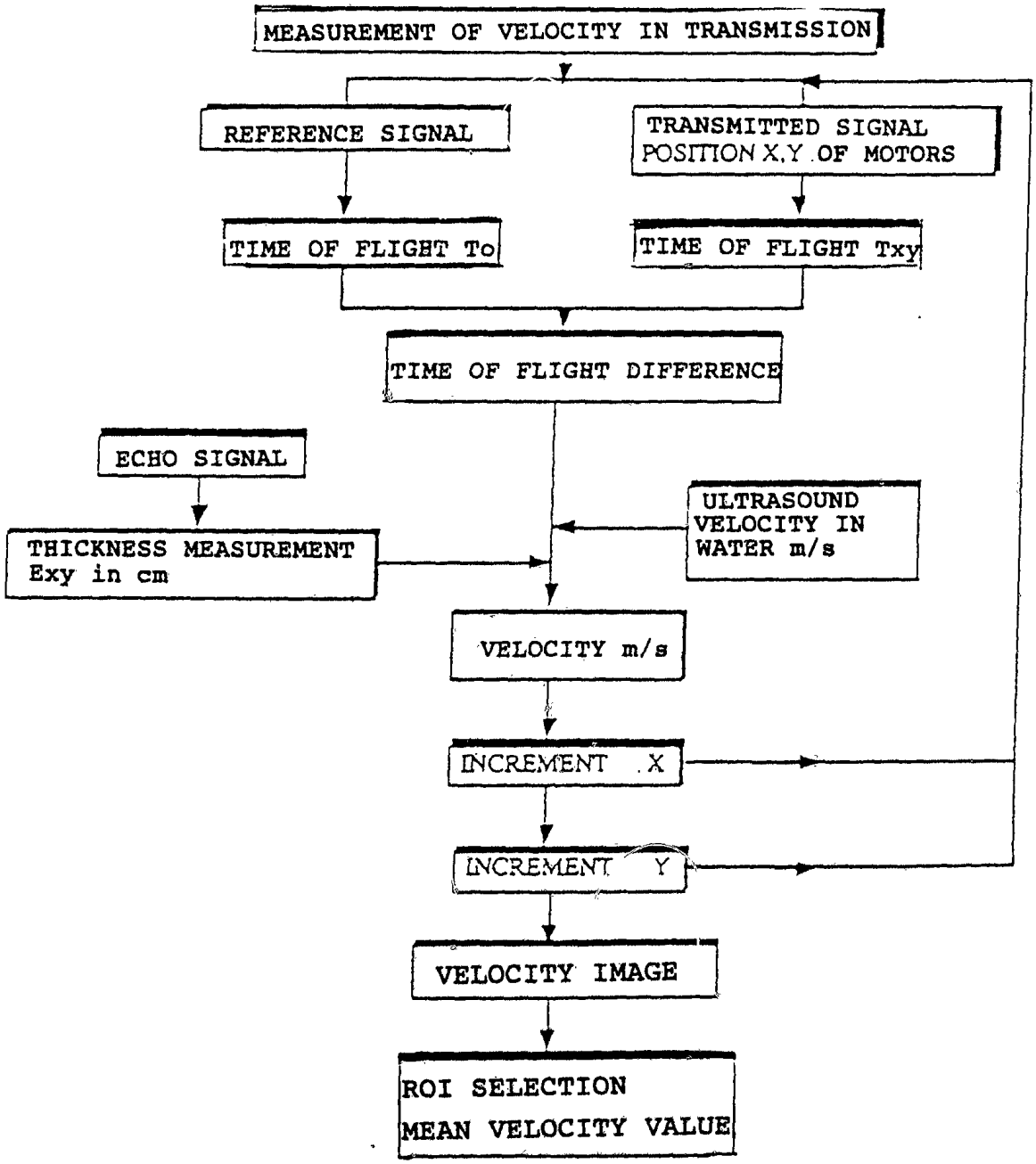
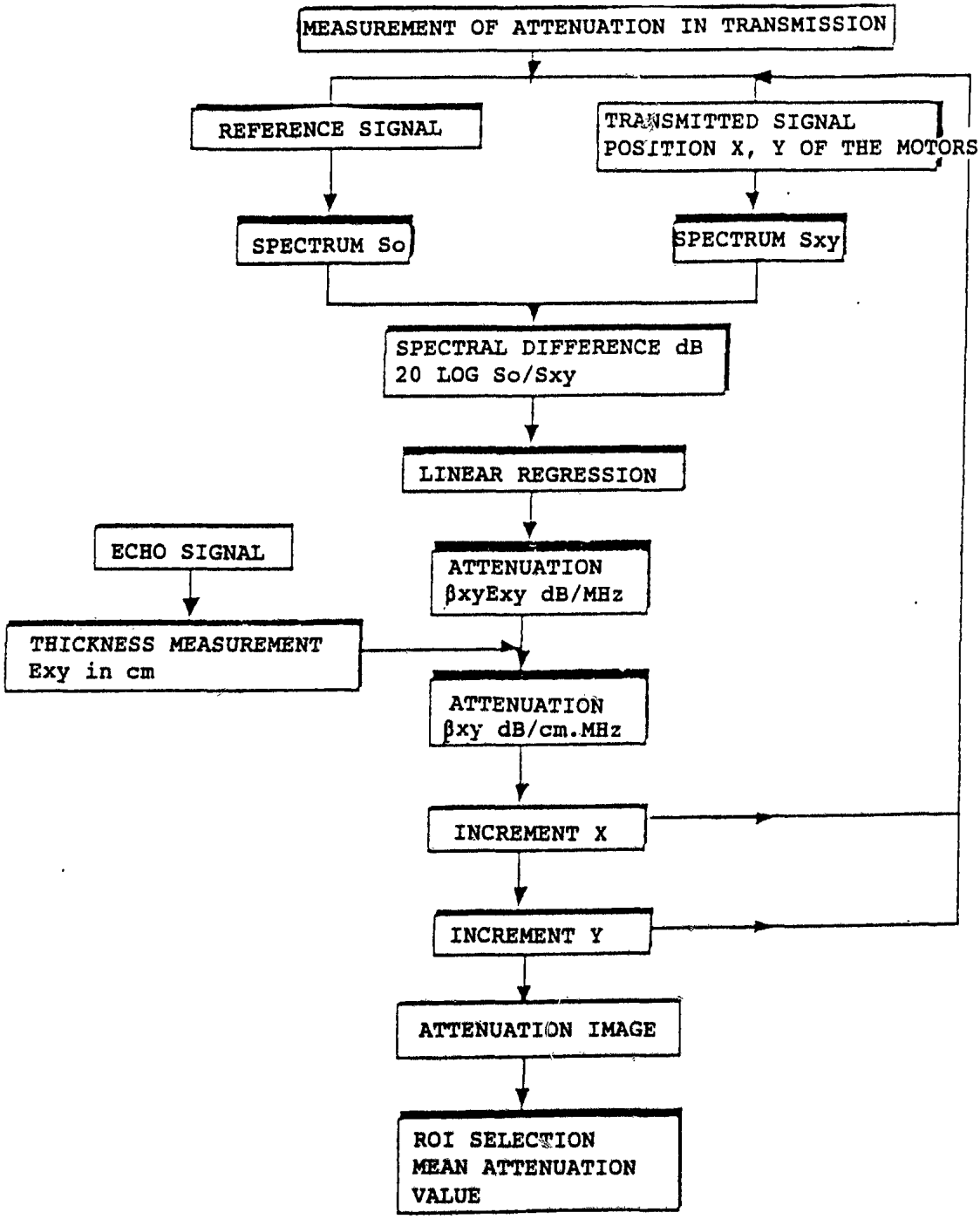

MEASUREMENT OF VELOCITY IN TRANSMISSION
REFERENCE SIGNAL
TRANSMITTED SIGNAL
POSITION X,Y OF MOTORS
TIME OF FLIGHT To
TIME OF FLIGHT Txy
TIME OF FLIGHT DIFFERENCE
ECHO SIGNAL
ULTRASOUND
VELOCITY IN
WATER m/s
THICKNESS MEASUREMENT
Exy in cm
VELOCITY m/s
INCREMENT X
INCREMENT Y
VELOCITY IMAGE
ROI SELECTION
MEAN VELOCITY VALUE

FIG. 10


MEASUREMENT OF ATTENUATION IN TRANSMISSION
REFERENCE SIGNAL
TRANSMITTED SIGNAL
POSITION X, Y OF THE MOTORS
SPECTRUM So
SPECTRUM Sxy
SPECTRAL DIFFERENCE dB
20 LOG So/Sxy
LINEAR REGRESSION
ECHO SIGNAL
ATTENUATION
βxyExy dB/MHz
THICKNESS MEASUREMENT
Exy in cm
ATTENUATION
βxy dB/cm.MHz
INCREMENT X
INCREMENT Y
ATTENUATION IMAGE
ROI SELECTION
MEAN ATTENUATION
VALUE

INTERNATIONAL SEARCH REPORT

Inv oral Application No
PCT/FR 95/00376

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61B8/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61B G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO,A,90 01296 (BOARD OF REGENT, THE UNIVERSITY OF TEXAS SYSTEM) 22 February 1990	1,5,8-10
Y	see page 8, line 20 - page 9, line 5	2-4
A	see page 18, line 9 - page 24; claim 23; tables 3-5F	6,7

Y	PHYSICS IN MEDICINE & BIOLOGY, vol. 35, no. 10, October 1990 BRISTOL, GB, pages 1387-1396, J.A.EVANS ET AL 'ultrasonic attenuation and velocity in bone' see page 1387, line 19 - page 1388, line 7	2,4

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 June 1995	17.07.95
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	**Authorized officer** Weihs, J

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INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/FR 95/00376

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	PROCEEDINGS OF IEEE 1990 ULTRASONICS SYMPOSIUM, vol. 3, 4 December 1990 HONOLULU, US, pages 1367-1370, N.CHUBACHI ET AL 'measurement of bone properties by ultrasound to develop diagnostic equipment' see page 1367, right column, line 23 - page 1368, left column, line 14; tables 1,2 -----	3,4

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INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/FR 95/00376

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9001296	22-02-90	US-A-	5038787	13-08-91
		AU-A-	4062289	05-03-90
		EP-A-	0428595	29-05-91
		US-A-	5197475	30-03-93

RAPPORT DE RECHERCHE INTERNATIONALE

De le internationale No
PCT/FR 95/00376

A. CLASSEMENT DE L'OBJET DE LA DEMANDE
CIB 6 A61B8/08

Selon la classification internationale des brevets (CIB) ou à la fois selon la classification nationale et la CIB

B. DOMAINES SUR LESQUELS LA RECHERCHE A PORTE

Documentation minimale consultée (système de classification suivi des symboles de classement)
CIB 6 A61B G01N

Documentation consultée autre que la documentation minimale dans la mesure où ces documents relèvent des domaines sur lesquels a porté la recherche

Base de données électronique consultée au cours de la recherche internationale (nom de la base de données, et si cela est réalisable, termes de recherche utilisés)

C. DOCUMENTS CONSIDERES COMME PERTINENTS

Catégorie *	Identification des documents cités, avec, le cas échéant, l'indication des passages pertinents	no. des revendications visées
X	WO,A,90 01296 (BOARD OF REGENT, THE UNIVERSITY OF TEXAS SYSTEM) 22 Février 1990	1,5,8-10
Y	voir page 8, ligne 20 - page 9, ligne 5	2-4
A	voir page 18, ligne 9 - page 24; revendication 23; tableaux 3-5F	6,7

Y	PHYSICS IN MEDICINE & BIOLOGY, vol. 35, no. 10, Octobre 1990 BRISTOL, GB, pages 1387-1396, J.A.EVANS ET AL 'ultrasonic attenuation and velocity in bone' voir page 1387, ligne 19 - page 1388, ligne 7	2,4

	-/--	

[X] Voir la suite du cadre C pour la fin de la liste des documents

[X] Les documents de familles de brevets sont indiqués en annexe

* Catégories spéciales de documents cités:

"A" document définissant l'état général de la technique, non considéré comme particulièrement pertinent

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"T" document ultérieur publié après la date de dépôt international ou la date de priorité et n'appartenenant pas à l'état de la technique pertinent, mais cité pour comprendre le principe ou la théorie constituant la base de l'invention

"X" document particulièrement pertinent; l'invention revendiquée ne peut être considérée comme nouvelle ou comme impliquant une activité inventive par rapport au document considéré isolément

"Y" document particulièrement pertinent; l'invention revendiquée ne peut être considérée comme impliquant une activité inventive lorsque le document est associé à un ou plusieurs autres documents de même nature, cette combinaison étant évidente pour une personne du métier

"&" document qui fait partie de la même famille de brevets

1

Date à laquelle la recherche internationale a été effectivement achevée	Date d'expédition du présent rapport de recherche internationale
26 Juin 1995	17. 07. 95

Nom et adresse postale de l'administration chargée de la recherche internationale	Fonctionnaire autorisé
Office Européen des Brevets, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Weihs, J

Formulaire PCT/ISA/210 (deuxième feuille) (juillet 1992)

C.(suite) DOCUMENTS CONSIDERES COMME PERTINENTS

Catégorie *	Identification des documents cités, avec, le cas échéant, l'indication des passages pertinents	no. des revendications visées
Y	PROCEEDINGS OF IEEE 1990 ULTRASONICS SYMPOSIUM, vol. 3, 4 Décembre 1990 HONOLULU, US, pages 1367-1370, N.CHUBACHI ET AL 'measurement of bone properties by ultrasound to develop diagnostic equipment' voir page 1367, colonne de droite, ligne 23 - page 1368, colonne de gauche, ligne 14; tableaux 1,2	3,4

RAPPORT DE RECHERCHE INTERNATIONALE

Demande internationale No
PCT/FR 95/00376

Document brevet cité au rapport de recherche	Date de publication	Membre(s) de la famille de brevet(s)		Date de publication
WO-A-9001296	22-02-90	US-A-	5038787	13-08-91
		AU-A-	4062289	05-03-90
		EP-A-	0428595	29-05-91
		US-A-	5197475	30-03-93