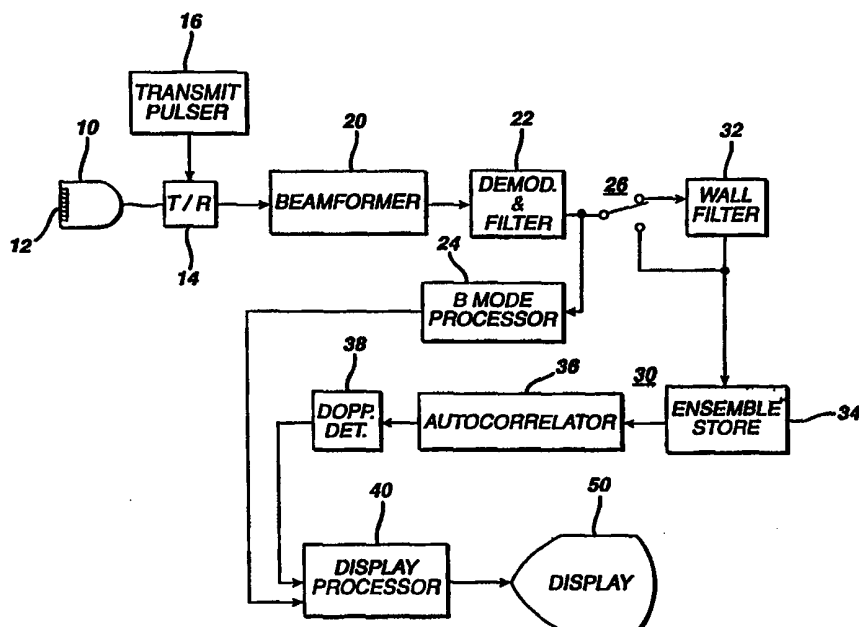




INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(21) International Application Number: PCT/IB99/00876 (22) International Filing Date: 14 May 1999 (14.05.99) (30) Priority Data: 09/080,881 18 May 1998 (18.05.98) US (71) Applicant: KONINKLIJKE PHILIPS ELECTRONICS N.V. [NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL). (71) Applicant (for SE only): PHILIPS AB [SE/SE]; Kottbygatan 7, Kista, S-164 85 Stockholm (SE). (72) Inventors: LOUPAS, Thanasis; Prof. Holstlaan 6, NL-5656 AA Eindhoven (NL). POWRIE, Charles; Prof. Holstlaan 6, NL-5656 AA Eindhoven (NL). CRITON, Aline, L.; Prof. Holstlaan 6, NL-5656 AA Eindhoven (NL). (74) Agent: LOTTIN, Claudine; Prof. Holstlaan 6, NL-5656 AA Eindhoven (NL).		(81) Designated States: JP, NO, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: METHOD FOR OPERATING AN ULTRASONIC DIAGNOSTIC IMAGING SYSTEM



(57) Abstract

The Doppler imaging of blood flow or slowly moving tissue at high frame rates of display is performed by oversampled acquisition of a Doppler ensemble from the body and display of Doppler information within a display range of Doppler values which is less than the range defined by said rate of oversampling. Preferably, Doppler information is acquired at the highest PRF for the depth of Doppler imaging. An embodiment of the present invention performs Doppler estimation by autocorrelation or spectral analysis which operates upon nonadjacent samples in the Doppler ensemble.

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Method for operating an ultrasonic diagnostic imaging system.

Field of the Invention

The invention relates to a method for operating an ultrasonic diagnostic imaging system and, in particular, a Doppler ultrasonic diagnostic imaging system.

Background of the Invention

5 The ultrasonic pulse echo imaging of structures, whereby received echo signals are amplitude detected and arranged in an image in consideration of their time of flight, is commonly referred to as B mode imaging. B mode imaging can be done at relatively high frame rates of display, since only one transmit pulse is needed for each image line of the display. Following transmission of an ultrasonic beam in a given direction, a sequence of
10 echoes is received from along the beam direction, from the near field to the far field. The time between transmit pulses is the time required to receive echoes from the greatest image depth in the beam direction. The time required to gather echoes for a complete image is approximately equal to (a) the total number of lines required to form the image multiplied by (b) the time between pulses. This means that all of the image lines for an image with a maximum depth of
15 10 cm can be acquired more quickly than a like number of lines of an image with a maximum depth of 20 cm. Consequently, the greater the depth of the image, the longer the time to acquire the image data and hence the slower the frame rate.

 The frame rate of display for B mode imaging, variable as it may be, is still considerably faster than the frame rate of display for Doppler images such as power Doppler
20 and colorflow images. This is because each Doppler image line must be interrogated a number of times in order to estimate the Doppler shift at points along the line. Each interrogation along the line acquires a full line of echo data, and the set of samples acquired over time for each point on the image line is referred to as an ensemble. The ensembles of data are needed to estimate the Doppler shift by fast Fourier transform or autocorrelation at each point along the
25 line. The number of transmit pulses required to gather a full ensemble of samples reduces the frame rate of display below that required to acquire the same image frame for B mode display.

 The frame rate of display can decline even further when the user is applying Doppler to image slow rates of bloodflow or tissue movement inside the body. This is because

the ensemble transmit pulse rate, referred to as the pulse repetition frequency or PRF, must be dropped so as to adequately sample the slow motion of flow or movement.

Summary of the Invention

5 A number of techniques involving the time-multiplexed interleaving of ensemble acquisition along a number of image lines have been proposed to address this problem. While making better use of the available imaging time, these techniques have not been able to dramatically improve the frame rate of display for slow flow conditions.

It would be desirable to augment these techniques with others which are able to detect slow flow conditions while maintaining a high frame rate of display.

10 It is a purpose of the present invention to propose a method to provide both an improved display rate and improved noise performance of Doppler estimation as compared with conventional techniques.

This problem is solved by a method according to Claim 1.

15 According to the principle of the invention, the Doppler processing is performed by autocorrelation between pairs of nonadjacent signals in an ensemble sequence.

A computer program product for performing the steps of the method of the invention is claimed in Claim 7.

Brief description of the Drawings

20 The invention is described hereafter in detail in reference to diagrammatic drawings. In the drawings:

FIGURE 1 illustrates in block diagram form an ultrasonic diagnostic imaging system constructed in accordance with the principles of the present invention;

FIGURE 2 illustrates an ultrasound image with a color box as produced by an embodiment of the present invention;

25 FIGURES 3 and 4 are phase diagrams illustrating the operation of the present invention; FIGURE 2a illustrates a color bar for the ultrasound image of FIGURE 2;

FIGURE 5 illustrates Doppler processing in accordance with the principles of the present invention; and

30 FIGURE 6 spectral Doppler processing in accordance with the principles of the present invention.

Description of the embodiments

Referring first to FIGURE 1, an ultrasonic diagnostic imaging system constructed in accordance with the principles of the present invention is shown in block diagram form. An ultrasonic probe 10 includes an array transducer 12 which transmits pulsed

beams of ultrasonic waves into the body and receives echoes reflected back to the transducer from cells and tissues in the body. The transmission by the probe is controlled by a transmit pulser 16, connected to the probe by a transmit/receive (T/R) switch 14, which determines the waveform characteristics and times of transmission by elements of the transducer array
5 necessary to transmit and focus the desired ultrasonic beam in a given direction. Following each pulsed transmission by the transducer array echoes are returned over time from increasing depths along the beam direction, referred to herein as a "line" of echo information. Each line of echoes is coupled by the T/R switch 14 to a beamformer 20, which delays and combines echo components from the individual elements of the array 12 to form a sequence of
10 coherent echo information along the line. The coherent echo information is demodulated to a desired intermediate or base band of frequencies and filtered by a demodulator and filter circuit 22.

The lines of coherent echo data may then be directed along several paths for processing. One path directs the echoes to a B mode processor 24, where the echoes are
15 amplitude detected and processed, then coupled to a display processor 40 for assembly and display of an ultrasonic B mode image on an image display 50. The B mode image will display the tissue structure in the region of the body being imaged, and may be displayed alone or in combination with Doppler information depicting motion in the imaged region. For Doppler display the lines of echo information may be applied to a wall filter which eliminates
20 low frequency, large amplitude echo information from slow moving or stationary structures such as the walls of the heart or blood vessels. The remaining information is echo information from moving fluids such as bloodflow. An ensemble of lines of bloodflow information is Doppler processed by a Doppler processor 30 and coupled to the display processor 40 where the speed, intensity or other detected characteristic of bloodflow is color-coded and overlaid or
25 blended with the structural B mode image. Such an image is commonly referred to as a colorflow display in the case of color-coded velocity, or a power Doppler display in the case of color-coded Doppler signal intensity.

The Doppler processor 30 may employ different processing techniques such as fast Fourier transform (FFT) processing or correlation processing. In a preferred embodiment
30 of the present invention autocorrelation processing is used. An ensemble of samples from each point on a Doppler image line, typically ranging from 2 to 16 samples per ensemble, is stored in an ensemble store 34. An ensemble of fewer samples may be used for display of moving tissue due to the high signal to noise ratio of tissue echoes and the fact that the wall filter is bypassed. The sample data is stored in quadrature I,Q form. An autocorrelator then multiplies

adjacent samples in the sequence of samples in complex conjugate form and sums the products to produce a result in the form of $I' + jQ'$. Mathematically the autocorrelation process can be expressed as

$$X' = \sum_{k=1}^{n-1} X_{k+1} \cdot X_k^* \quad \dots\dots\dots(1)$$

- 5 where $X_k = I_k + jQ_k$ and n is the number of samples in the sequence. From the complex result the Doppler phase shift ϕ_D is calculated by a Doppler detector 38 as the arc tangent of the quotient of Q' and I' , or

$$\phi_D = \tan^{-1} \frac{Q'}{I'} \quad \dots\dots\dots(2)$$

The Doppler frequency shift f_D is determined by multiplying the phase shift ϕ_D by the PRF and

- 10 dividing by 2π :

$$f_D = \phi_D \frac{PRF}{2\pi} \quad \dots\dots\dots(3)$$

The velocity of the motion is then estimated from the Doppler velocity equation

$$v = \frac{f_D c}{2f_o \cos \theta} \quad \dots\dots\dots(4)$$

by assuming f_o to be the center frequency of the transmitted waveform.

- 15 In an embodiment of the present invention two dimensional autocorrelation is used as described in U.S. Patent 5,386,830. The velocities thus determined may be used in a colorflow display by overlaying or blending Doppler color-coded pixels with the B mode image or in a spectral Doppler display of spectral lines. Other Doppler data such as variance, acceleration and power may also be determined from this Doppler data and displayed on the
- 20 display 50.

When a user desires to view the motion of tissue, such as the motion of the heart walls of the beating heart, the received echo information bypasses the wall filter as symbolically shown by the switch 26, so that the relatively higher amplitude, lower velocity echoes from moving tissue will be processed and displayed. The moving tissue Doppler

25 information is processed by the Doppler processor 30 in the same manner as the bloodflow information. However, since the velocity of moving tissue is generally lower than the velocity of bloodflow, the PRF is usually set to a lower frequency so as to adequately sample the lower frequency motion. The lower PRF setting means that a greater amount of time is required to gather each ensemble of echoes, and hence all of the echoes needed to form a complete image.

- 30 This necessarily decreases the frame rate of display, the rate at which new images are

produced and displayed. A low frame rate of display detracts from the desired performance of the realtime image display.

In accordance with one aspect of the present invention, a high frame rate of display is maintained by operating the system at a higher PRF than the display PRF chosen by the user, preferably at the maximum possible PRF for the selected maximum depth of the Doppler display. By way of illustration FIGURE 2 shows a B mode image 60 of a region of the body being imaged by a probe located at the top 64 of the image. The user has the ability to define a color box 62 within the image in which motion will be detected and displayed. Conventionally the color box 62 may be set to any size and location in the image 60, including occupying the entire image 60. The time required to acquire a line of Doppler echoes from the illustrated box 62 is a function of the maximum depth $D_{\max}$ of the box:

$$T = \frac{2D_{\max}}{c} \dots\dots\dots(5)$$

where c is the speed of sound in the body. This translates into a pulse repetition interval of:

$$PRI \geq T = \frac{2D_{\max}}{c} \text{ and a maximum PRF of}$$

$$PRF_{\max} = \frac{c}{2D_{\max}} \dots\dots\dots(6)$$

When the acquisition PRF is PRF_a and the desired display PRF is PRF_d , from equation (2) the phase shift corresponding to the acquisition PRF_a is $\phi_a = \tan^{-1} \frac{Q'}{I'}$. The phase shift corresponding to the display PRF_d is obtained by rescaling according to:

$$\phi_d = \phi_a \cdot \frac{PRF_a}{PRF_d} \dots\dots\dots(7)$$

where if $|\phi_d| > \pi$, the value is remapped back to the range $[-\pi, \pi]$. For example when $\phi_d = 5\pi/4$, the value is remapped to $\phi_d = -3\pi/4$. Thus, the Doppler frequency corresponding to the display PRF_d is:

$$f_D = \phi_d \frac{PRF_d}{2\pi} \dots\dots\dots(8)$$

As an example of this aspect of the present invention, suppose that a given depth $D_{\max}$ will permit a maximum PRF of 5000 Hz. But suppose that the user desires to see a lower velocity of motion and has set the ultrasound system's PRF to 4000 Hz for display. In this scenario the system of the present invention could acquire Doppler data at the maximum

acquisition rate of 5000 Hz, but would rescale the color display to show the 4000 Hz range that the user requested. This is illustrated by the phase diagram of FIGURE 3. This phase diagram shows the 0 Hz origin at the right, and frequencies extending to +2500 Hz in the counterclockwise direction and extending to -2500 Hz in the clockwise direction from the origin. This is the range of the PRF used to acquire Doppler ensembles, 5000 Hz. However, the displayed PRF requested by the user in this example is only 4000 Hz, which is indicated by the +2000 Hz and -2000 Hz lines on the phase diagram. To display this requested range over the full length of the color bar 70, shown adjacent to the image 60 in FIGURE 2a, the requested range of 4000 Hz is scaled in proportion to its relation to the acquisition range of 5000 Hz. This particular example will use a scale factor of 5000/4000, or 5/4. The range of values from -2000 Hz to +2000 Hz is scaled by this factor to display the desired display PRF over the full color bar 70. This is indicated in FIGURE 2a, where the color bar is shown extending between +20cm/sec and -20 cm/sec (the 4000 Hz range) instead of the acquisition range of +25 cm/sec to -25 cm/sec shown by the dashed extensions to the solid color bar 70.

In the foregoing example, the frame rate of display is improved by 25%, since $5000/4000=125\%$.

It is always possible that the velocity of the motion being displayed will from time to time momentarily exceed the display range requested by the user, resulting in aliased color values in the Doppler display. Techniques are known for detecting these aliasing conditions and displaying appropriate colors for the conditions. A preferred embodiment of the present invention will similarly display aliasing conditions, which is straightforward since conditions which exceed the requested display PRF range may not exceed the acquisition PRF range. FIGURE 4 illustrates such a situation, where the acquisition PRF range extends from -2000 Hz to +2000 Hz, and the user has requested a display range of -1000 Hz to +1000 Hz. In this example the ultrasound system has momentarily detected a velocity of +1200 Hz, which is beyond the upper limit of the requested display range. The user would expect this excessive velocity to alias, and an embodiment of the present invention can produce an aliased result by relocating the +1200 Hz vector for display at its alias location of -800 Hz, resulting in its color display as a -800 Hz value. Thus, the display will alias for the selected display range just as the user expects. A preferred embodiment of the present invention can provide both an improved display rate and improved noise performance of Doppler estimation as compared with conventional techniques. Referring to the illustration of FIGURE 5, an autocorrelation implementation of the present invention is depicted. As mentioned above, the conventional autocorrelation technique will operate upon adjacent samples in a sequence of received echoes

from a point in the body. In accordance with another aspect of the present invention, autocorrelation is performed using nonadjacent samples of oversampled Doppler data. In FIGURE 5 the acquisition PRF is 4000 Hz, ranging from -2000 Hz to +2000 Hz as shown by the phase diagram at the top of the drawing. A PRF of 4000 Hz implies a PRI interval
 5 between transmit pulses of 1/4000 Hz, or 0.25 msec, as shown by the arrows representing 16 sampling times at a given location in the body. In this example the user desires to image the motion of slow moving tissue and has called for a display PRF of 400 Hz, ranging from -200 Hz to +200 Hz as shown in the phase diagram. To produce this display PRF samples separated by the desired display PRI of 1/400 Hz are used in the autocorrelation equation to produce a
 10 sequence of frequency shift estimates f_D , which are summed as called for by the autocorrelation process. Thus, the autocorrelation process can be expressed as :

$$X' = \sum_{k=1}^{n-PRF_a/PRF_d} X_{k+PRF_a/PRF_d} \bullet X_k^* \dots\dots\dots(9)$$

where PRF_a/PRF_d is the ratio of the acquisition PRF_a to the display PRF_d . As FIGURE 5 illustrates, the oversampling accomplished by the high acquisition PRF enables a series of
 15 Doppler frequency shift estimates f_{D1} , f_{D2} , f_{D3} etc. to be calculated in rapid succession. These multiple estimates are summed to produce a more noise-immune estimate as compared to use of samples acquired at the display PRF alone. The rapid succession of calculations means that the frame rate of display can be a function of the higher acquisition PRF rather than the lower display PRF, providing desirably higher realtime frame rates of display.

Both techniques of the present invention can be used simultaneously, if desired. For instance, if the desired display PRF is 400 Hz and the maximum acquisition PRF is 4000 Hz, an ensemble can be acquired at the 4000 Hz rate and autocorrelation performed on the products of sample pairs(X_m) and (X_{m+4}) to produce Doppler phase estimates at 1000 Hz. These estimates can then be rescaled by a factor of 2.5 to yield the desired display range of
 25 400 Hz.

The principles of the present invention are also applicable to spectral Doppler and color M-mode displays. FIGURE 6 illustrates a sequence of samples acquired at intervals of T_a from a given sample volume location. Spectral lines are produced by use of nonadjacent samples as shown below the sample arrows. A first spectral line, col. 1, is formed by Fourier
 30 transform processing (in the case of spectral Doppler; autocorrelation is preferred for color M-mode processing) of the first, third, fifth, etc. samples. The next spectral line, col. 2, is formed by Fourier transform processing (or autocorrelation) of the second, fourth, sixth, etc. samples. For each spectral line another successive nonadjacent grouping of samples is used. As

demonstrated above in the example of color Doppler, more rapid spectral line display rate results in comparison with conventional processing of adjacent samples.

The present invention can be employed in combination with known techniques for time-multiplexing of the acquisition of Doppler ensembles from a group of lines simultaneously. The acquisition techniques of the present invention can be time-multiplexed, if desired. But one problem which arises when time-multiplexing the ensemble acquisition of a group of lines is that a significant temporal discontinuity develops at the boundary between line groups. Such a problem can be easily avoided with the present invention, since the interval during which a line is rapidly oversampled is relatively short. Thus, little is to be gained by time-multiplexing the acquisition of Doppler data in the practice of the present invention, and time-multiplexing can be disregarded to avoid the temporal discontinuities and the visual banding they produce in the image.

However, time-multiplexed acquisition and the oversampling technique of the present invention can be advantageously combined if desired. For example, suppose that two lines are to be acquired by time-multiplexing, the maximum acquisition PRF (from equation (6)) is 5000 Hz, and the desired display PRF is 2000 Hz. Since, for time-multiplexing, the acquisition PRF must be an integer multiple of the display PRF, conventional time-multiplexed acquisition would employ a multiplexing factor of 2, resulting in:

$$\text{PRF}_a = 4000 \text{ Hz, and } \text{PRF}_d = 2000 \text{ Hz}$$

But with the use of the present invention,

$\text{PRF}_a = 5000 \text{ Hz}$, resulting in the sampling of each line by a multiplexing factor of 2 at a $\text{PRF}_{\text{line}} = 2500 \text{ Hz}$. Doppler estimates would be taken at the 2500 PRF of each sequence using equation (1) then, using equations (7) and (8) (see FIGURES 3 and 4), remapped to the desired 2000 Hz display PRF_d . With the higher acquisition PRF_a of 5000 Hz, there will be a 25% improvement in the display frame rate over time-multiplexing alone.

It is to be noted that, in an ultrasonic examination apparatus, the functions of the imaging method according to the invention may be performed by a suitably programmed computer or by one or several special purpose processors having circuit means that are arranged to perform said functions.

Claims:

1. A method for operating an ultrasonic diagnostic imaging system to image the motion of substances inside the body by Doppler techniques, including an ultrasonic probe which is operable by a user to transmit ultrasonic waves at a controllable rate (PRF) and to receive Doppler signals from a point in the body in response to said transmitted waves which
5 sample the effects of motion at said point, a Doppler processor which processes said Doppler signals for display of motion, and a display which displays motion comprising the steps of:
controlling said probe to transmit ultrasonic waves at a transmit PRF;
receiving a sequence of Doppler signals from a given point in the body over
time in response to said transmit PRF;
10 Doppler processing said sequence by autocorrelation processing between pairs of nonadjacent signals in said sequence; and
displaying motion determined by said autocorrelation processing.
2. A method as claimed in Claim 1, wherein said nonadjacent signals which are
15 combined by autocorrelation are chosen in correspondence with a desired range of motional display.
3. A method as claimed in Claim 1, wherein said display of motion corresponds to a display PRF and the separation of said nonadjacent signals combined by autocorrelation
20 processing corresponds to said display PRF.
4. A method as claimed in Claim 3, wherein said separation of said nonadjacent signals corresponds to the ratio of said transmit PRF to said display PRF.
- 25 5. A method as claimed in Claim 1, wherein said nonadjacent signals are combined by complex multiplication and summation.
6. A method as claimed in Claim 5, wherein said autocorrelation processing is of the form

$$X' = \sum_{k=1}^{n-PRF_a/PRF_d} X_{k+PRF_a/PRF_d} \bullet X_k^* \quad \text{where } X \text{ is a Doppler signal, } n \text{ is the number of signals in the}$$

sequence, PRF_a is the transmit PRF, and PRF_d is the display PRF.

7. A computer program product comprising a set of instructions for carrying out a
- 5 method as claimed in one of Claims 1 to 6.

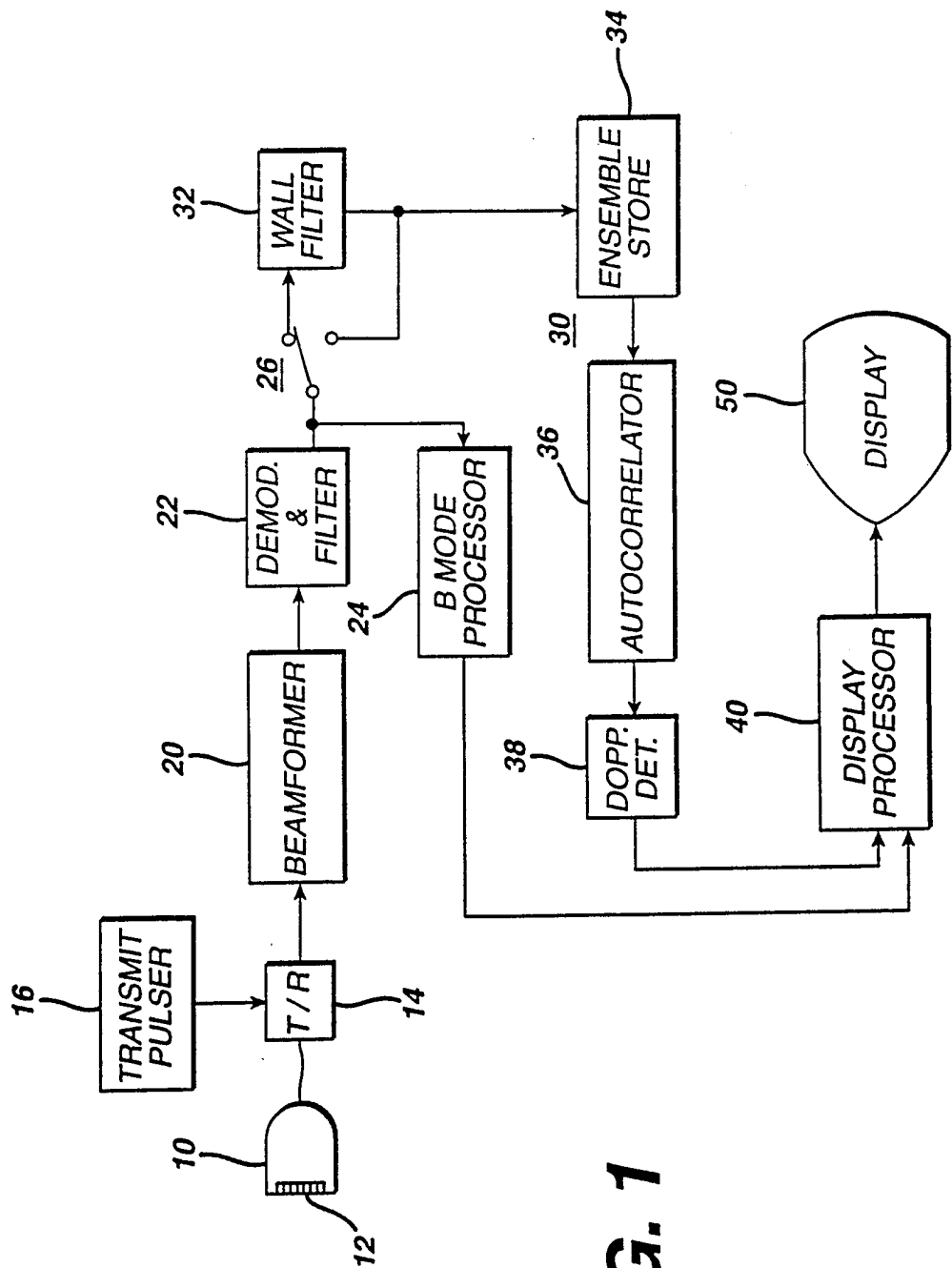


FIG. 1

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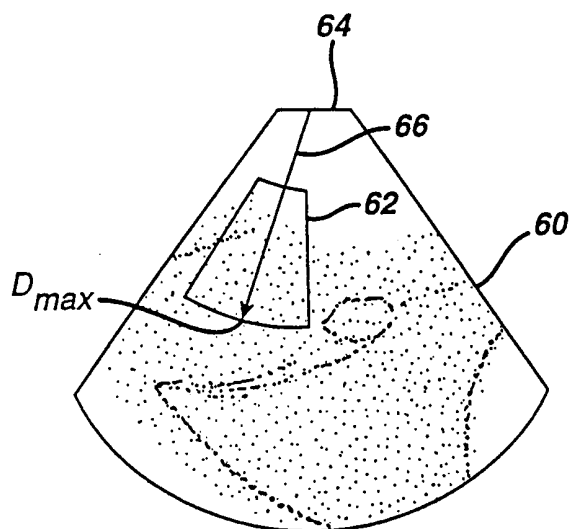
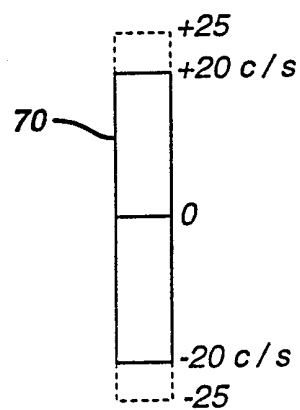
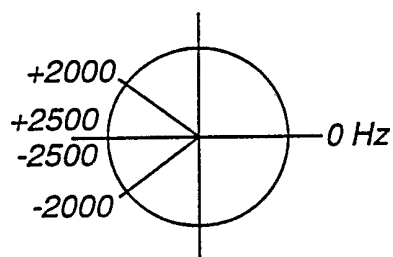
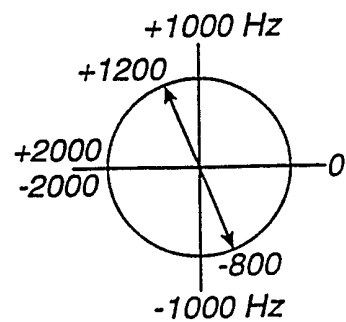
FIG. 2**FIG. 2a****FIG. 3****FIG. 4**

FIG. 5

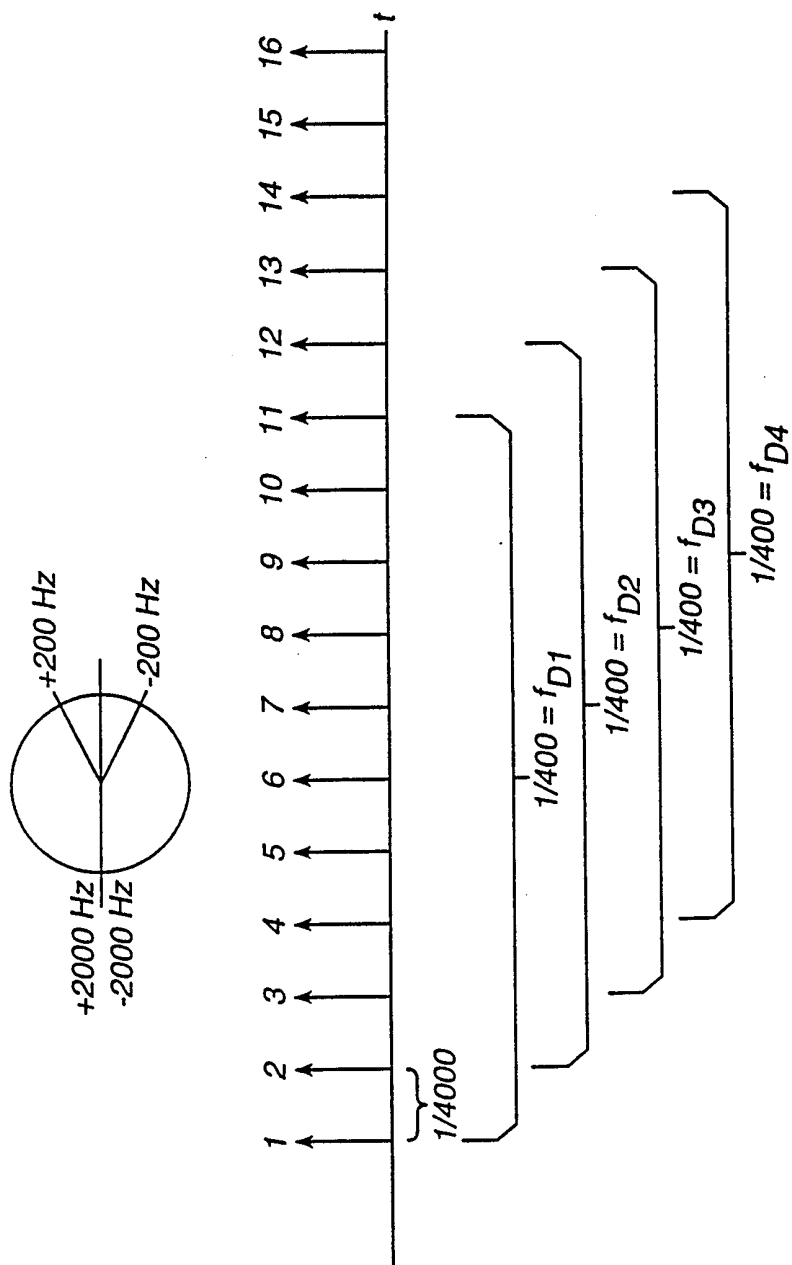
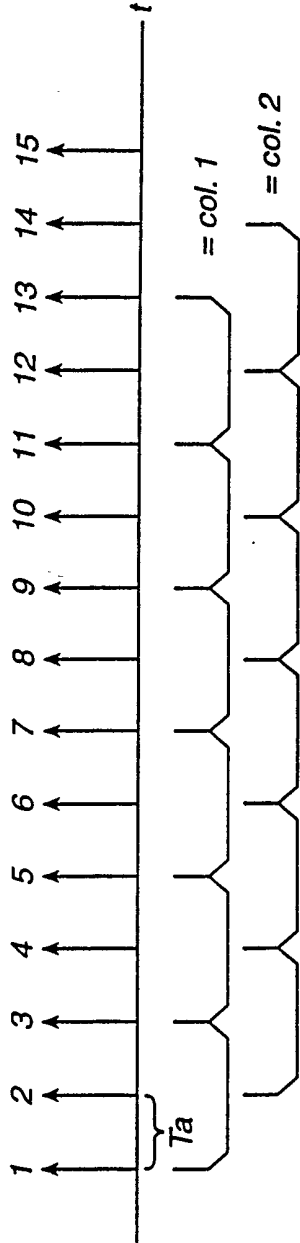


FIG. 6



INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB 99/00876

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: A61B 8/08, G01F 1/66, G01F 1/72

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)

IPC6: A61B, G01F

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

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, 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.
A	EP 0481691 A1 (ADVANCED TECHNOLOGY LABORATORIES, INC.), 22 April 1992 (22.04.92), page 4, line 48 - line 58 --	1-6
A	US 5363851 A (ANNE L. HALL), 15 November 1994 (15.11.94), column 5, line 58 - column 6, line 20 --	1-6
D,A	US 5386830 A (JEFFRY E. POWERS ET AL.), 7 February 1995 (07.02.95), abstract -- -----	1-6

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

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

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"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

13 October 1999

Date of mailing of the international search report

15-10-1999

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB 99/00876

Box I Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 7
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

The claim relates to a set of instructions, however no instructions are described. It is therefore unclear what is meant.

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐

The additional search fees were accompanied by the applicant's protest.

☐

No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

28/09/99

International application No.
PCT/IB 99/00876

Patent document cited in search report			Publication date	Patent family member(s)		Publication date
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