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(54) ULTRASOUND DISPLAY OF DISPLACEMENT

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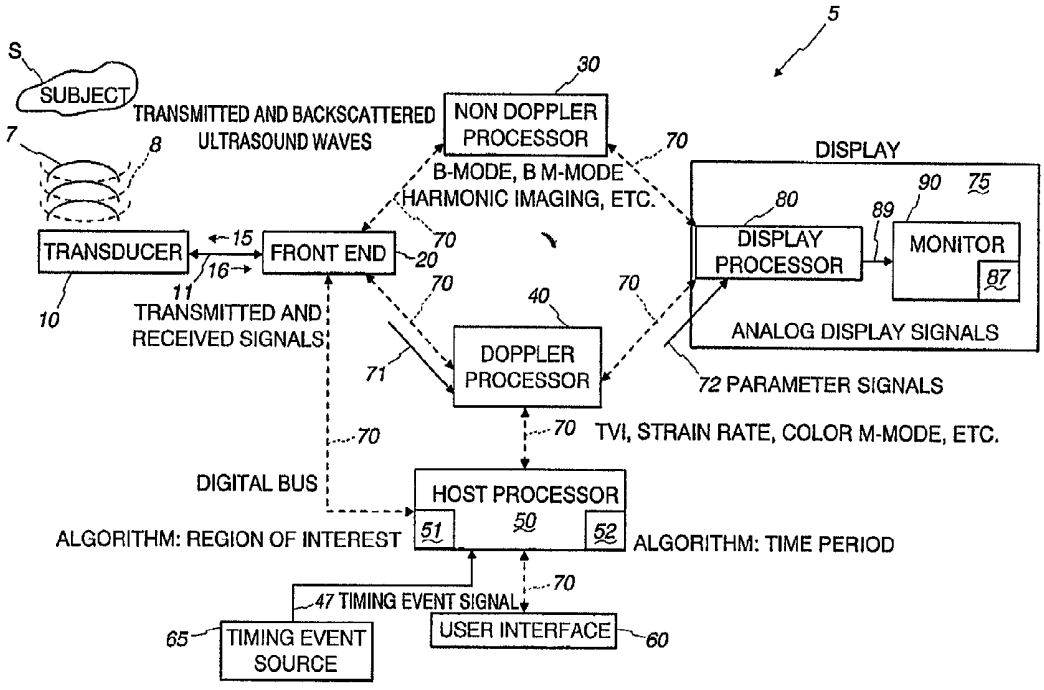
(57) ABSTRACT

An ultrasound machine that generates a color representation of moving structure, such as cardiac wall tissue within a region of interest, and is displayed on a monitor. The color representation is generated by displaying at least one color characteristic related to a set of signal values of the structure, such as velocity or strain rate. The related feature of the set of signal values is mapped to the color characteristic by an apparatus comprising a front-end that generates received signals in response to backscattered ultrasound waves. A Doppler processor generates a set of signal values representing a spatial set of values of the moving structure. A host processor embodies a tracking function and a time integration function to generate tracked movement parameter profiles and displacement parameter values over a time period corresponding to sampled anatomical locations within the region of interest. The displacement parameter values are then mapped to color characteristic signals. A display processor maps the values of the color characteristic signals to the displacement parameter values, representing the moving structure, to display a color representation, on a monitor.



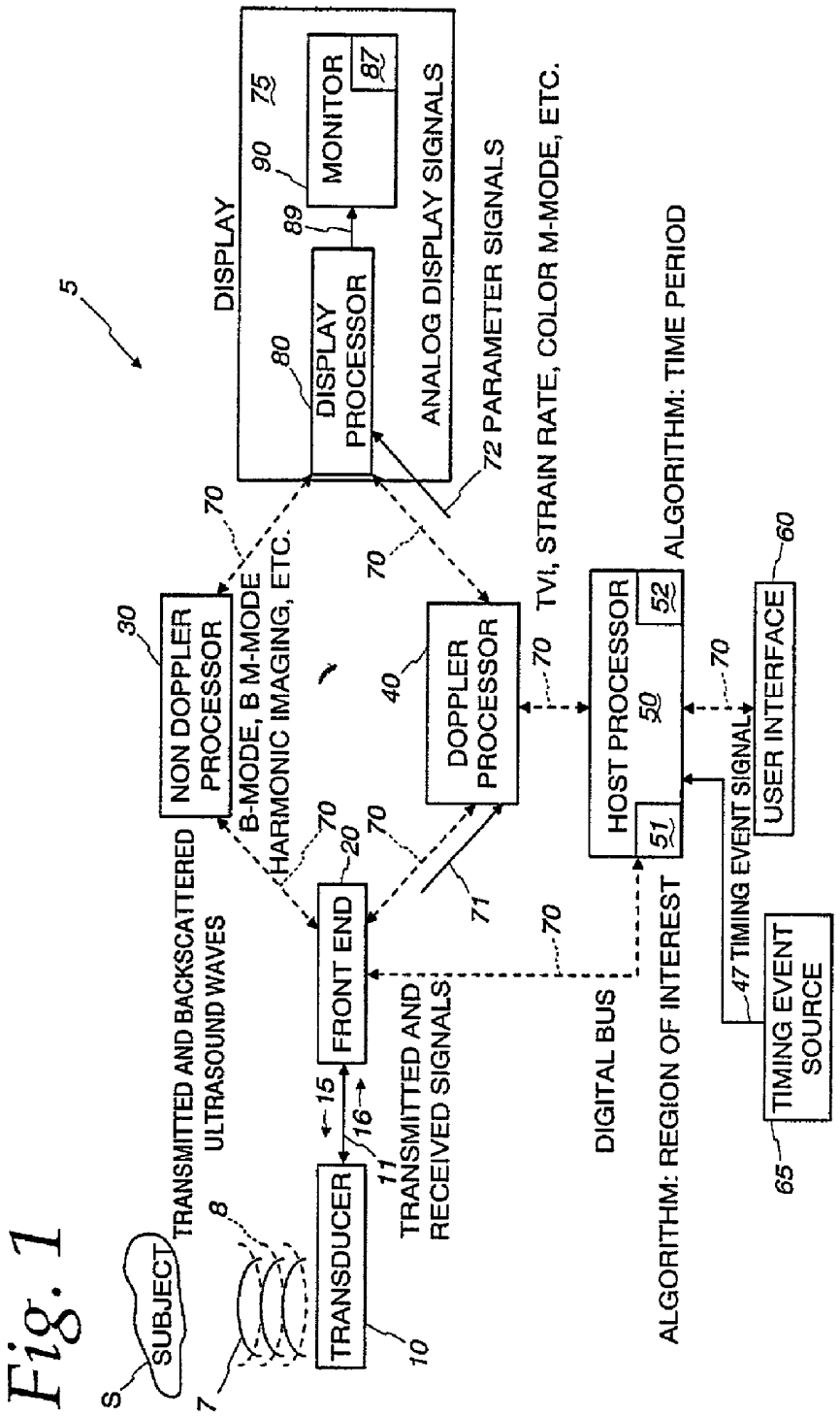

5
DISPLAY
75
90
MONITOR
87
89
DISPLAY PROCESSOR
80
ANALOG DISPLAY SIGNALS
72 PARAMETER SIGNALS
70
30
NON DOPPLER PROCESSOR
B-MODE, B M-MODE
HARMONIC IMAGING, ETC.
40
DOPPLER PROCESSOR
TVI, STRAIN RATE, COLOR M-MODE, ETC.
HOST PROCESSOR
50
51
52
ALGORITHM: TIME PERIOD
60
USER INTERFACE
47 TIMING EVENT SIGNAL
TIMING EVENT SOURCE
65
DIGITAL BUS
ALGORITHM: REGION OF INTEREST
20
FRONT END
15
16
11
TRANSMITTED AND RECEIVED SIGNALS
TRANSDUCER
10
TRANSMITTED AND BACKSCATTERED ULTRASOUND WAVES
8
7
SUBJECT
S
71

Fig. 1

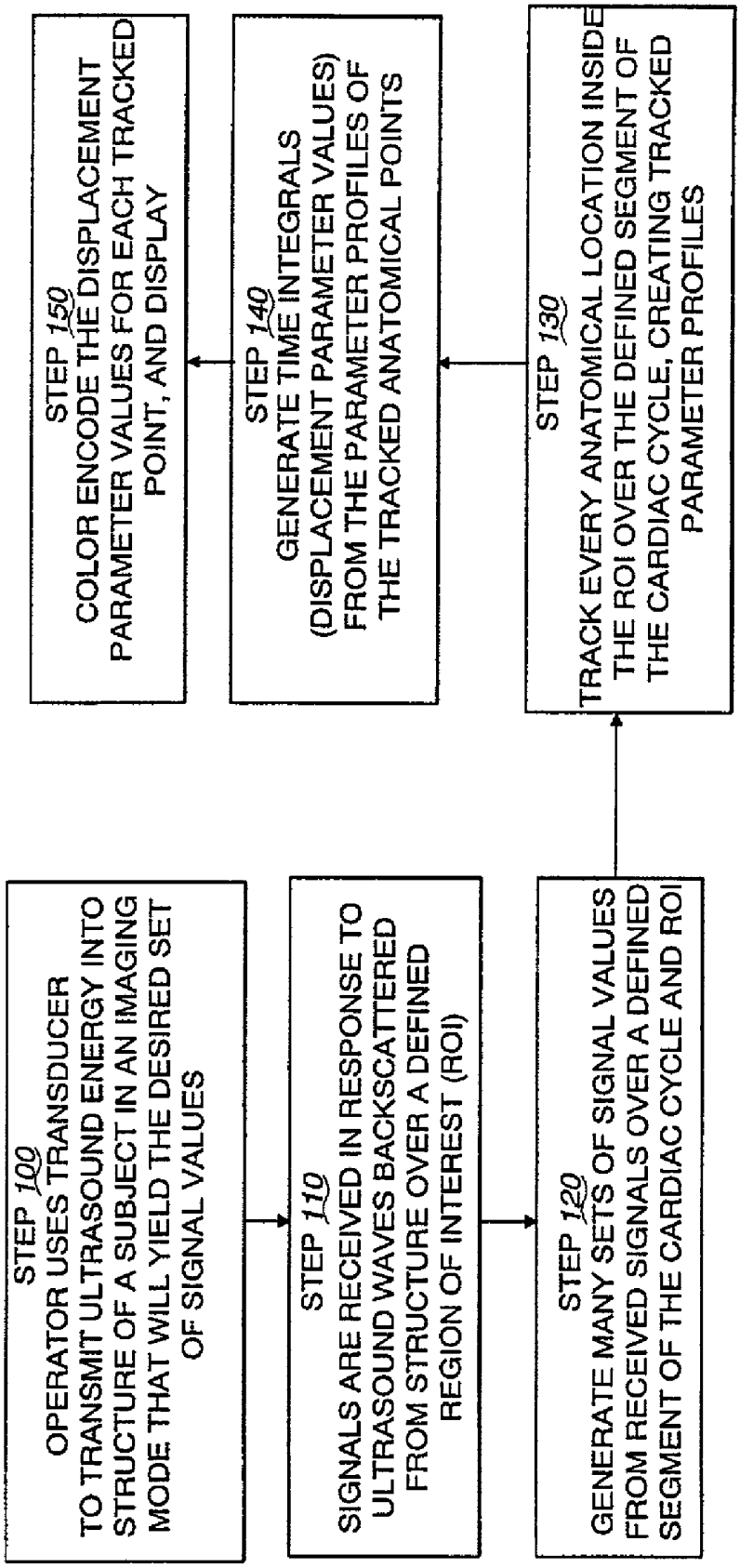

STEP 100
OPERATOR USES TRANSDUCER TO TRANSMIT ULTRASOUND ENERGY INTO STRUCTURE OF A SUBJECT IN AN IMAGING MODE THAT WILL YIELD THE DESIRED SET OF SIGNAL VALUES
STEP 110
SIGNALS ARE RECEIVED IN RESPONSE TO ULTRASOUND WAVES BACKSCATTERED FROM STRUCTURE OVER A DEFINED REGION OF INTEREST (ROI)
STEP 120
GENERATE MANY SETS OF SIGNAL VALUES FROM RECEIVED SIGNALS OVER A DEFINED SEGMENT OF THE CARDIAC CYCLE AND ROI
STEP 130
TRACK EVERY ANATOMICAL LOCATION INSIDE THE ROI OVER THE DEFINED SEGMENT OF THE CARDIAC CYCLE, CREATING TRACKED PARAMETER PROFILES
STEP 140
GENERATE TIME INTEGRALS (DISPLACEMENT PARAMETER VALUES) FROM THE PARAMETER PROFILES OF THE TRACKED ANATOMICAL POINTS
STEP 150
COLOR ENCODE THE DISPLACEMENT PARAMETER VALUES FOR EACH TRACKED POINT, AND DISPLAY

Fig. 2

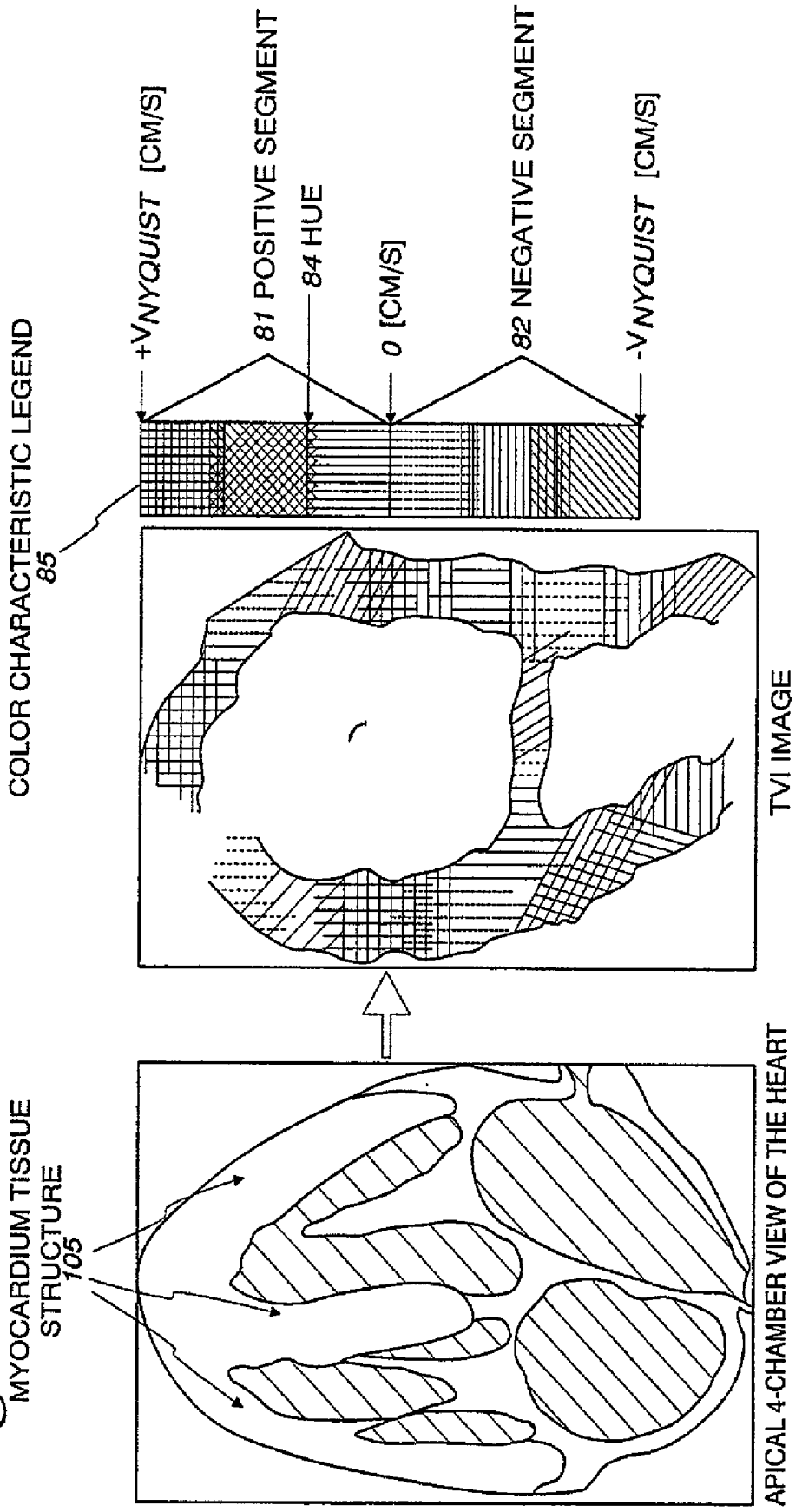

COLOR CHARACTERISTIC LEGEND
85
+VNYQUIST [CM/S]
81 POSITIVE SEGMENT
84 HUE
0 [CM/S]
82 NEGATIVE SEGMENT
-VNYQUIST [CM/S]
TVI IMAGE
MYOCARDIUM TISSUE STRUCTURE
105
APICAL 4-CHAMBER VIEW OF THE HEART

Fig. 3

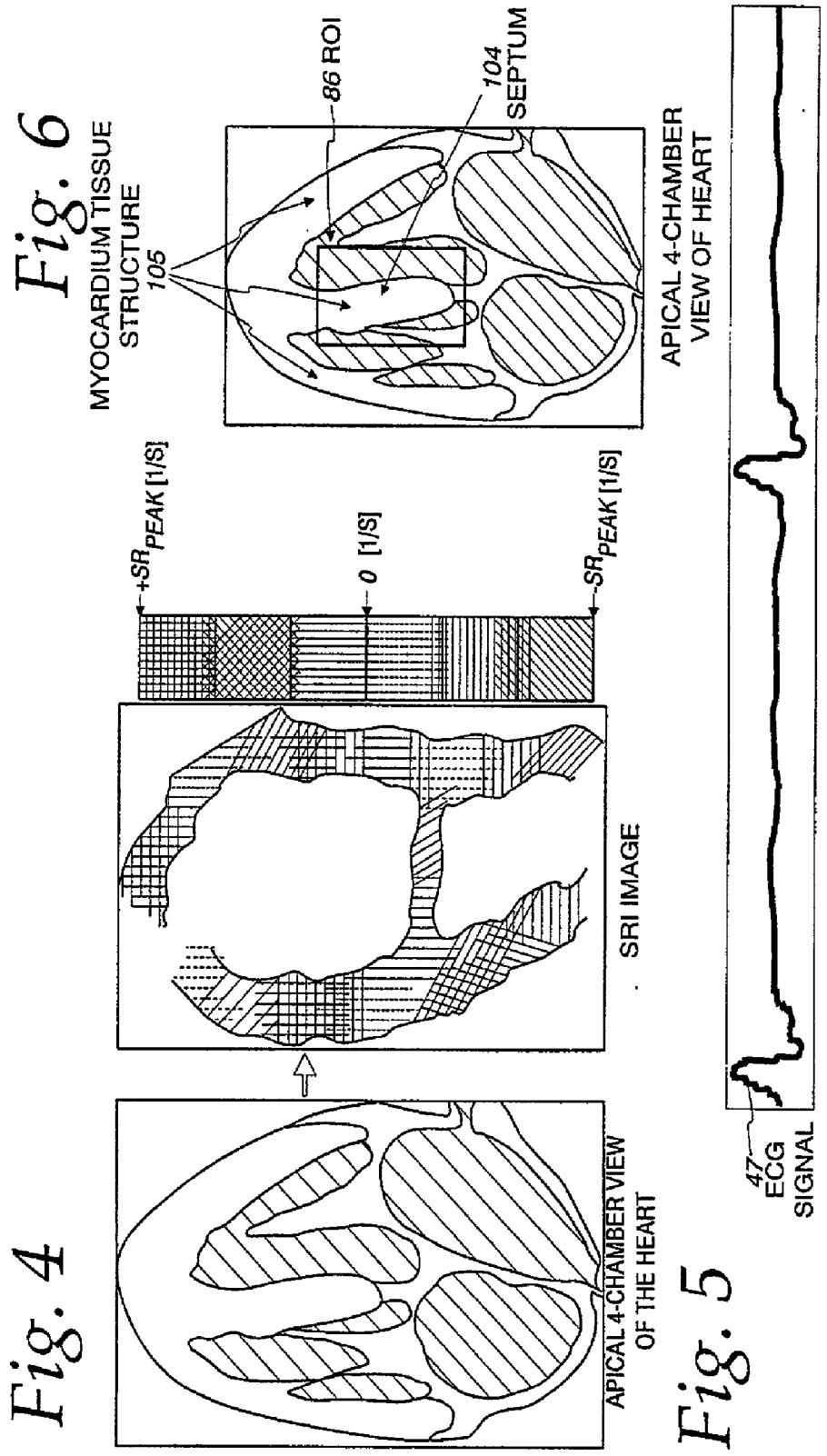


Fig. 4

Fig. 5

Fig. 6

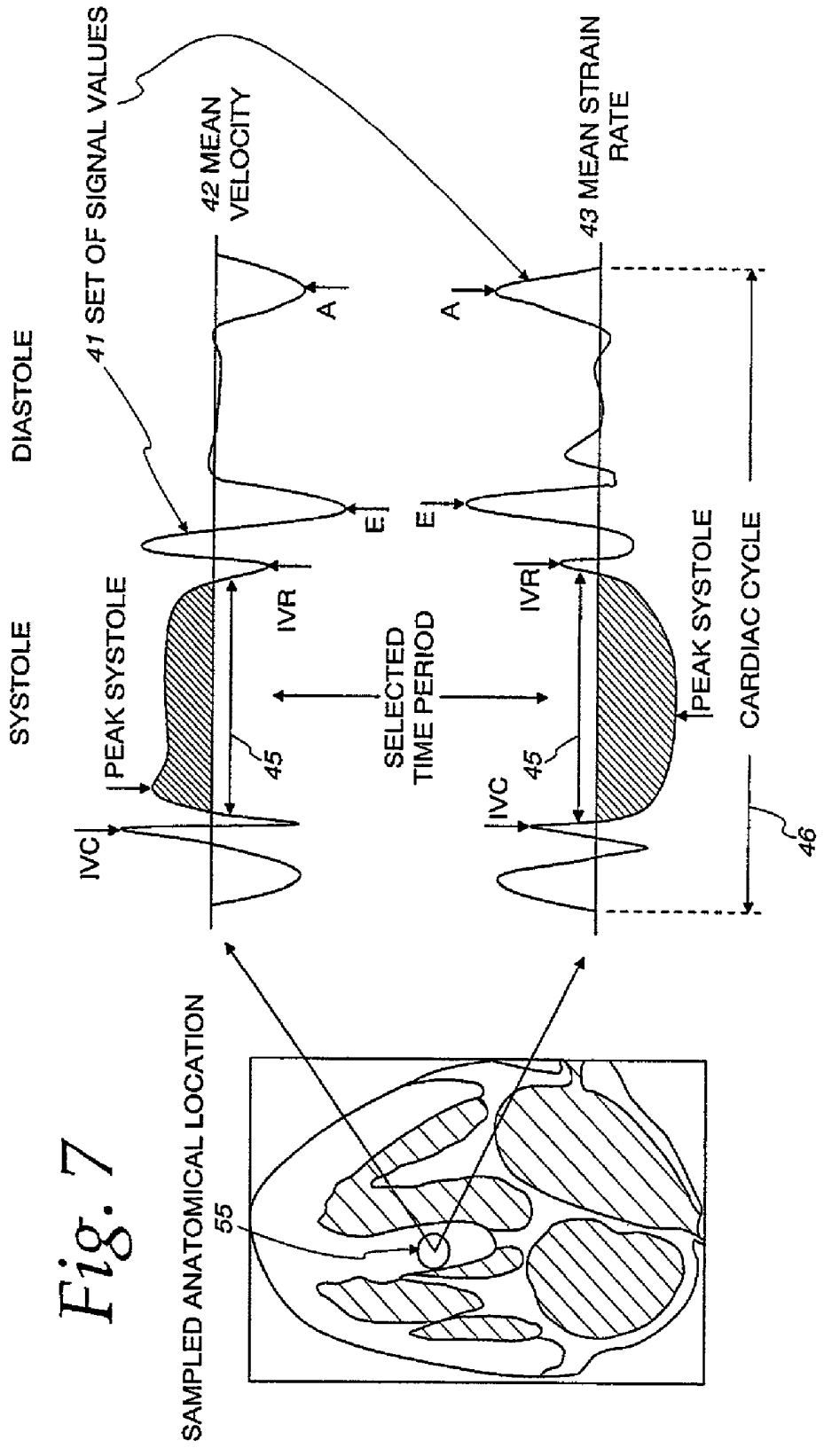

SYSTOLE
DIASTOLE
41 SET OF SIGNAL VALUES
42 MEAN VELOCITY
43 MEAN STRAIN RATE
A
E
IVC
PEAK SYSTOLE
IVR
45
SELECTED TIME PERIOD
CARDIAC CYCLE
46
SAMPLED ANATOMICAL LOCATION
55

Fig. 7

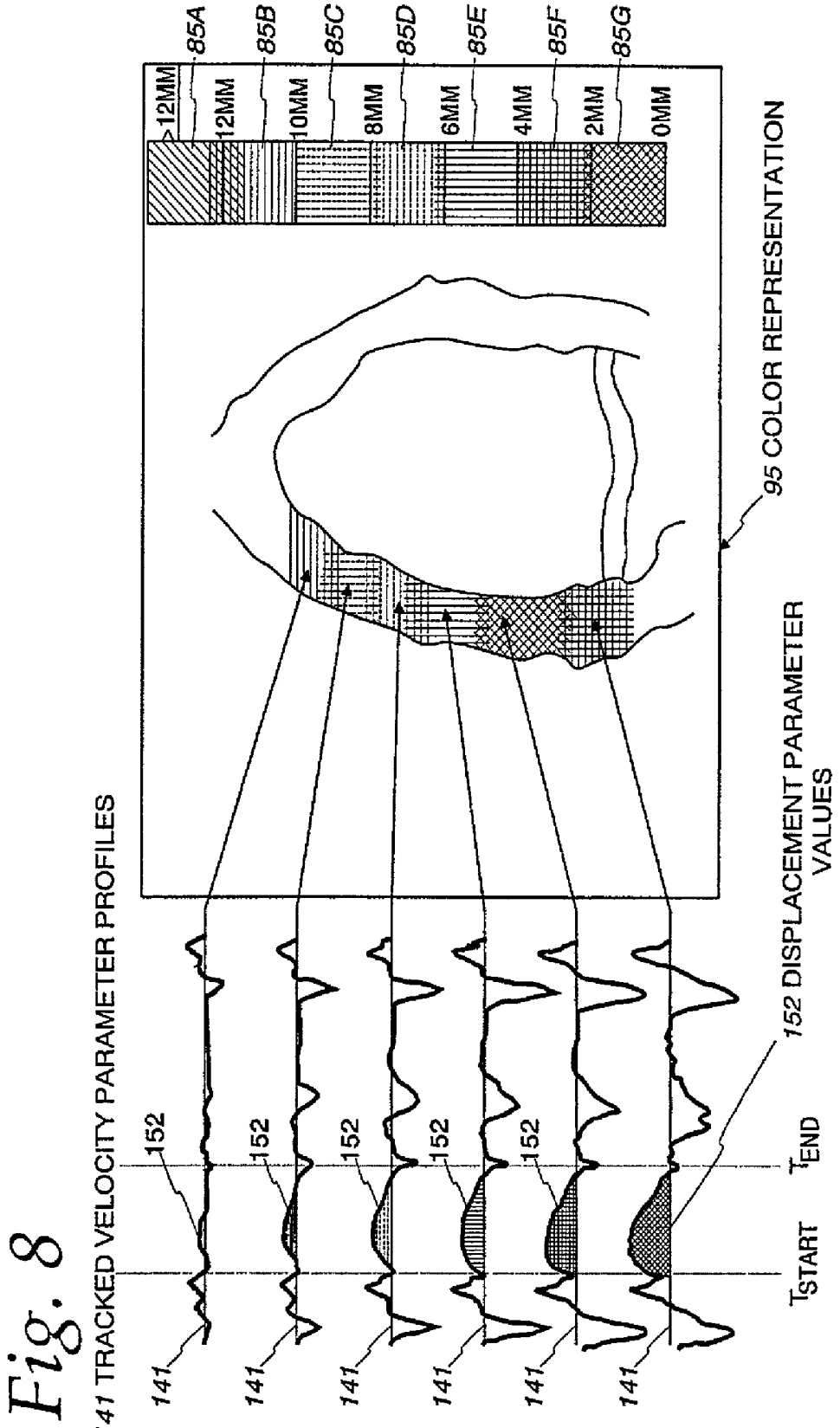

141 TRACKED VELOCITY PARAMETER PROFILES
152
141
T START
T END
152 DISPLACEMENT PARAMETER VALUES
95 COLOR REPRESENTATION
>12MM
12MM
10MM
8MM
6MM
4MM
2MM
0MM
85A
85B
85C
85D
85E
85F
85G

Fig. 8

Fig. 9

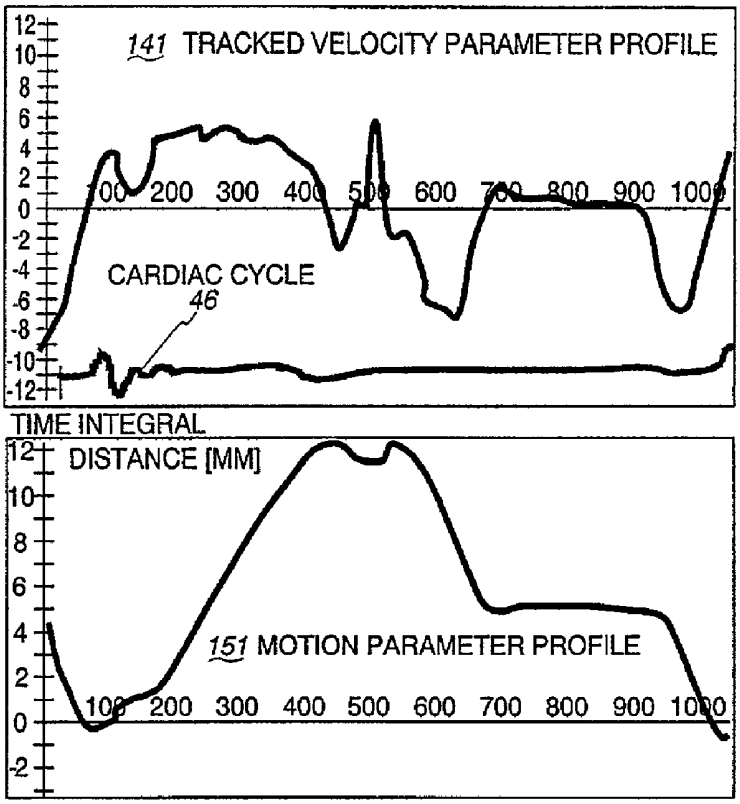
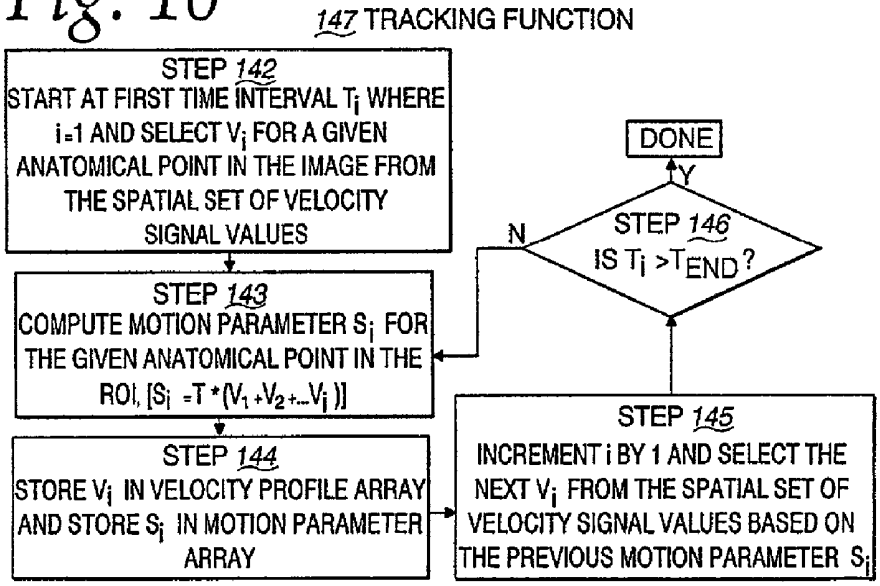

141 TRACKED VELOCITY PARAMETER PROFILE
CARDIAC CYCLE
46
TIME INTEGRAL
DISTANCE [MM]
151 MOTION PARAMETER PROFILE

Fig. 10


147 TRACKING FUNCTION
STEP 142
START AT FIRST TIME INTERVAL T_i WHERE i=1 AND SELECT V_i FOR A GIVEN ANATOMICAL POINT IN THE IMAGE FROM THE SPATIAL SET OF VELOCITY SIGNAL VALUES
STEP 143
COMPUTE MOTION PARAMETER S_i FOR THE GIVEN ANATOMICAL POINT IN THE ROI, $[S_i = T*(V_1+V_2+...V_i)]$
STEP 144
STORE V_i IN VELOCITY PROFILE ARRAY AND STORE S_i IN MOTION PARAMETER ARRAY
STEP 145
INCREMENT i BY 1 AND SELECT THE NEXT V_i FROM THE SPATIAL SET OF VELOCITY SIGNAL VALUES BASED ON THE PREVIOUS MOTION PARAMETER S_i
STEP 146
IS $T_i > T_{END}$?
N
Y
DONE

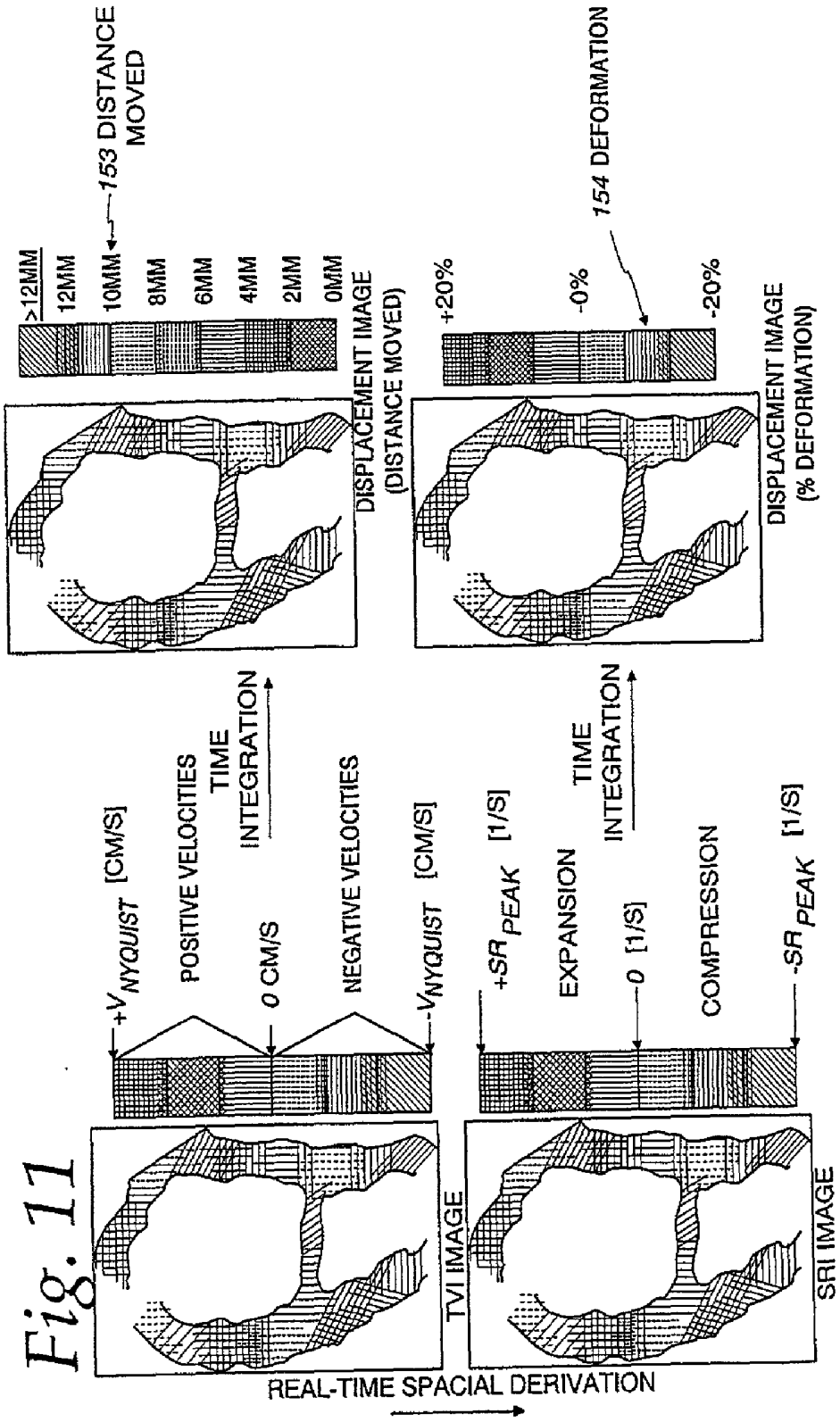

153 DISTANCE MOVED
>12MM
12MM
10MM
8MM
6MM
4MM
2MM
0MM
DISPLACEMENT IMAGE (DISTANCE MOVED)
154 DEFORMATION
+20%
-0%
-20%
DISPLACEMENT IMAGE (% DEFORMATION)
+V NYQUIST [CM/S]
POSITIVE VELOCITIES
TIME INTEGRATION
0 CM/S
NEGATIVE VELOCITIES
-V NYQUIST [CM/S]
+SR PEAK [1/S]
EXPANSION
TIME INTEGRATION
0 [1/S]
COMPRESSION
-SR PEAK [1/S]
TVI IMAGE
SRI IMAGE
REAL-TIME SPACIAL DERIVATION

Fig. 11

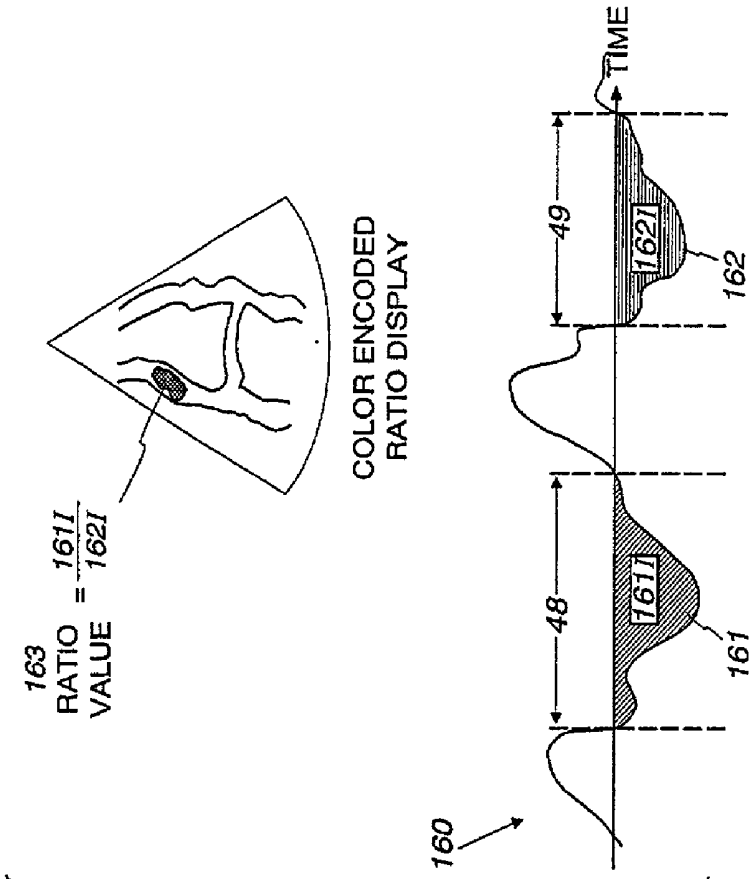

163
RATIO VALUE = 1611 / 1621
COLOR ENCODED RATIO DISPLAY
TIME
49
1621
162
48
1611
161
160

Fig. 12

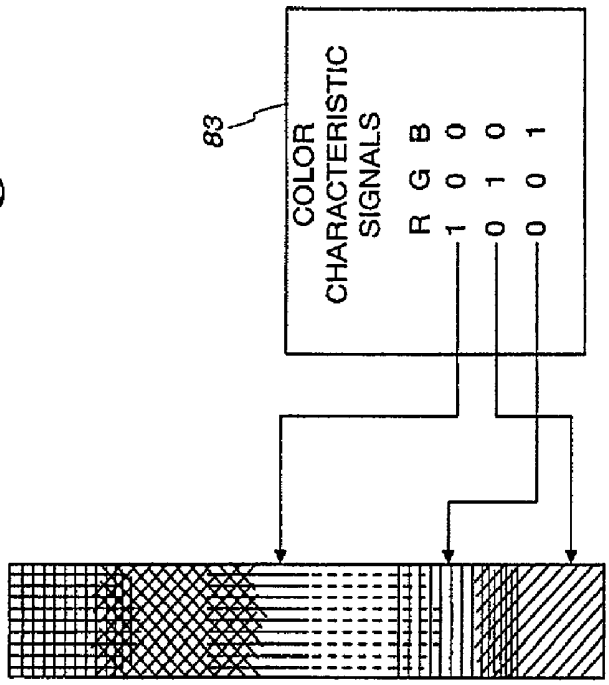

83
COLOR CHARACTERISTIC SIGNALS
R G B
1 0 0
0 1 0
0 0 1

Fig. 13

ULTRASOUND DISPLAY OF DISPLACEMENT

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The applicants claimed priority based on provisional application No. 60/297572 filed Jun. 12, 2001 in the names of Bjorn Olstad, Steinar Bjaerum, and Kjell Kristoffersen.

BACKGROUND OF INVENTION

[0002] Certain embodiments of the present invention relate to an ultrasound machine for displaying an image of moving structure. More particularly, certain embodiments relate to displaying displacement of moving structure such as distance moved and deformation.

[0003] Echocardiography is a branch of the ultrasound field that is currently a mixture of subjective image assessment and extraction of key quantitative parameters. Evaluation of cardiac wall function has been hampered by a lack of well-established parameters that may be used to increase the accuracy and objectivity in the assessment of, for example, coronary artery diseases. Stress echo is such an example. It has been shown that the subjective part of wall motion scoring in stress echo is highly dependent on operator training and experience. It has also been shown that inter-observer variability between echo-centers is unacceptably high due to the subjective nature of the wall motion assessment.

[0004] Much technical and clinical research has focused on the problem and has aimed at defining and validating quantitative parameters. Encouraging clinical validation studies have been reported, which indicate a set of new potential parameters that may be used to increase objectivity and accuracy in the diagnosis of, for instance, coronary artery diseases. Many of the new parameters have been difficult or impossible to assess directly by visual inspection of the ultrasound images generated in real-time. The quantification has required a post-processing step with tedious, manual analysis to extract the necessary parameters.

[0005] Academic work has been done for validation of peak, mean systolic velocities as an indicator of, for example, ischemia in stress echo. A related parameter to peak systolic motion is displacement calculated as a velocity time integral during systole. Similar related displacement parameters may be defined for any sub-interval of the cardiac cycle. Displacement parameters derived from the time integral of velocity measurements or strain rate measurements have very low noise content compared to peak detection and are, therefore, attractive parameters to use for quantitative assessment of wall function. Therefore, it may be useful to design a mechanization that makes it easy to visually assess displacement of cardiac wall tissue in a quantitative manner.

[0006] Much of the prior art describes techniques for color mapping estimated imaging parameters such as tissue velocity and strain rate. A fixed mapping of a continuous range of color hues is typically used to indicate positive velocities or strain rates and a second fixed mapping of a continuous range of color hues is used to indicate negative velocities or strain rates. This type of color encoding makes it easy to identify reversals in velocities or strain rates. However, the tissue velocity imaging (TVI) and strain rate imaging (SRI) modes and associated color mapping schemes in the prior art are not, by themselves, well suited for visual determination of other parameters, such as displacement measured as time integrated velocities or time integrated strain rates over a portion of the cardiac cycle.

[0007] A need exists for an approach to more easily visualize tissue displacement information, such as time integrated velocity and time integrated strain rate, in a two-dimensional dimensional ultrasound image.

SUMMARY OF INVENTION

[0008] An embodiment of the present invention provides an ultrasound system for generating an image responsive to moving cardiac structure by displaying color characteristics representative of tissue displacement.

[0009] An apparatus is provided in an ultrasound machine for generating an image responsive to moving structure within a region of interest of a subject and displaying a color characteristic representing displacement of the moving structure. In such an environment apparatus displaying the color characteristic comprises a front-end arranged to transmit ultrasound waves into a structure and then to generate received signals in response to ultrasound waves backscattered from the structure in the region of interest over a time period. A processor is responsive to the received signals to generate a parameter value representing displacement of the moving structure during the time period and is responsive to the parameter value to generate a color characteristic signal representative of the displacement. A display is arranged to display a color representation of the displacement in response to the color characteristic signal.

[0010] A method embodiment is also provided in an ultrasound machine for generating an image responsive to moving structure within a region of interest of a subject and for displaying a color characteristic representing displacement of the moving structure. In such an environment, the method for displaying the color characteristic comprises transmitting ultrasound waves into the structure and generating received signals in response to ultrasound waves backscattered from the structure in the region of interest over a time period. A parameter value representing displacement of the moving structure during the time period is generated in response to the received signals. A color characteristic signal, representative of the displacement, is generated in response to the parameter value. A color representation of the moving structure is displayed in response to the color characteristic signal.

[0011] Certain embodiments of the present invention afford an approach to visualize the color display of the displacement of moving structure with a degree of convenience and accuracy previously unattainable in the prior art.

BRIEF DESCRIPTION OF DRAWINGS

[0012] **FIG. 1** is a schematic block diagram of an ultrasound machine made in accordance with an embodiment of the present invention.

[0013] **FIG. 2** is a flowchart of a method performed, at least in part, by the machine shown in **FIG. 1** in accordance with an embodiment of the present invention.

[0014] **FIG. 3** includes a cross-sectional view of a heart, a corresponding tissue velocity image (TVI) generated by the machine in **FIG. 1**, and a color legend generated by the machine in **FIG. 1** that may be used to interpret the colors shown in the TVI image in accordance with an embodiment of the present invention.

[0015] **FIG. 4** includes a cross-sectional view of a heart, a corresponding strain rate image (SRI) generated by the machine in **FIG. 1**, and a color legend generated by the machine in **FIG. 1** that may be used to interpret the colors shown in the SRI image in accordance with an embodiment of the present invention.

[0016] **FIG. 5** illustrates an exemplary ECG signal that may be generated by a timing event source and used by the machine in **FIG. 1** to identify a time interval in accordance with an embodiment of the present invention.

[0017] **FIG. 6** is a schematic cross-sectional view of the human heart including myocardium tissue bounded by a region of interest (ROI) that is designated by the machine shown in **FIG. 1** under control of an operator in accordance with an embodiment of the present invention.

[0018] **FIG. 7** is a schematic cross-sectional view of the heart shown in **FIG. 6** also graphically representing mean velocity and mean strain rate profiles as a function of time, measured longitudinally in an apical view for a sampled anatomical location in accordance with an embodiment of the present invention.

[0019] **FIG. 8** is a graph illustrating time integrated velocity profiles and color encoding generated by the method shown in **FIG. 2**, together with an exemplary display of cardiac tissue using the color encoding in accordance with an embodiment of the present invention.

[0020] **FIG. 9** shows graphs of a tracked velocity parameter profile and a motion parameter profile generated by the tracking algorithm flowcharted in **FIG. 10** in accordance with an embodiment of the present invention.

[0021] **FIG. 10** is a flowchart of the longitudinal tracking function that generates the graphs shown in **FIG. 9** and is executed by the machine shown in **FIG. 1** in accordance with an embodiment of the present invention.

[0022] **FIG. 11** shows displays of tissue structure displacement generated by the machine in **FIG. 1** illustrating the relationship between TVI and SRI and the time integration of velocity and strain rate which is performed by the method shown in **FIG. 2** in accordance with an embodiment of the present invention.

[0023] **FIG. 12** is a graphic of a color characteristic legend and a signal diagram illustrating the color characteristic signals generated by the machine in **FIG. 1** in terms of RGB values and how these values relate to the color characteristic legend in accordance with an embodiment of the present invention.

[0024] **FIG. 13** is a graphic of a set of parameter signals and a ratio image generated from the set of parameter signals by the machine in **FIG. 1** in accordance with an embodiment of the present invention.

[0025] The foregoing summary, as well as the following detailed description of certain embodiments of the present invention, will be better understood when read in conjunction with the appended drawings. It should be understood, however, that the present invention is not limited to the arrangements and instrumentality shown in the attached drawings.

DETAILED DESCRIPTION

[0026] An embodiment of the present invention enables longitudinal tracking of moving structure and real time color visualization of displacement of the moving structure. As used herein, structure means non-liquid and non-gas matter, such as cardiac wall tissue. An embodiment of the present invention offers improved, real-time visualization and assessment of wall tissue function. The moving structure is characterized by a displacement parameter, which may be, for example, distance moved by the structure or deformation of the moving structure.

[0027] FIG **1**. a schematic block diagram of an ultrasound machine **5** made in accordance with an embodiment of the present invention. A transducer **10** is used to transmit ultrasound waves **7** (solid curves in **FIG. 1**) into a subject S by converting electrical analog signals **15** to ultrasonic energy, and to receive ultrasound waves **8** (dashed curves in **FIG. 1**) backscattered from the subject S by converting ultrasonic energy to analog electrical signals **16**.

[0028] A front-end **20** comprising a receiver, transmitter, and beamformer, is used to create the transmitted waveforms, beam patterns and receiver filtering techniques used for the various imaging modes. Front-end **20** performs the functions by converting digital data to analog data and vice versa. Front-end **20** interfaces at an analog interface **11** to transducer **10** and interfaces at a digital interface over a digital bus **70** to a non-Doppler processor **30** and a Doppler processor **40** and a host processor **50**. Digital bus **70** may comprise several digital sub-buses, each sub-bus having its own unique configuration and providing digital data interfaces to various parts of the ultrasound machine **5**.

[0029] Non-Doppler processor **30** comprises amplitude detection functions and data compression functions used for imaging modes such as B-mode, B M-mode, and harmonic imaging. Doppler processor **40** comprises clutter filtering functions and movement parameter estimation functions used for imaging modes such as tissue velocity imaging (TVI), strain rate imaging (SRI), and color M-mode. The two processors, **30** and **40**, accept digital data from the front-end **20**, process the data into sets of signal values **41**, and pass the values to processor **50** and/or a display **75** over digital bus **70**. The estimated values may be created using the received signals in frequency bands centered at the fundamental, harmonics, or sub-harmonics of the transmitted signals in a manner known to those skilled in the art.

[0030] Display **75** comprises scan-conversion functions, color mapping functions, and tissue/flow arbitration functions, performed by a display processor **80** which accepts digital parameter signals **72** from processors **30**, **40**, and **50**, processes, maps, and formats the digital data for display, converts the digital display data to analog display signals **89**, and passes the analog display signals **89** to a monitor **90**.

[0031] Monitor **90** accepts the analog display signals **89** from display processor **80** and displays the resultant image **87** to the operator on monitor **90**.

[0032] A user interface **60** allows user commands to be input by the operator to the ultrasound machine **5**. User

interface **60** comprises a keyboard, mouse, switches, knobs, buttons, track ball, and on screen menus (not shown).

[**0033**] Host processor **50** is the main, central processor of the ultrasound machine **5** and interfaces to various other parts of the ultrasound machine **5** through digital bus **70**. Host processor **50** executes the various data algorithms and functions for the various imaging modes. Digital data and commands may be transmitted and received between the host processor **50** and other various parts of the ultrasound machine **5**. The functions performed by processor **50** may be performed by multiple processors or may be integrated into processors **30**, **40**, or **80**, or any combination thereof.

[**0034**] Referring to **FIG. 2**, in step **100** an operator uses transducer **10** to transmit ultrasound energy into the appropriate anatomical structure, such as cardiac tissue **105** (see **FIG. 3**), of the subject in an imaging mode (such as TVI or SRI) that yields a desired set of signal values **41** (see **FIG. 7**) of the anatomical structure **105**. As shown in **FIG. 7**, the set of signal values **41** typically comprises longitudinal estimates of mean tissue velocity **42** or mean tissue strain rate **43** parameters. The specification herein uses the examples of tissue velocity imaging (TVI) and tissue strain rate imaging (SRI). Based on the specification herein, those skilled in the art may also provide an embodiment that employs other estimated parameters that form a set of signal values.

[**0035**] Referring to **FIG. 3**, in TVI mode a fixed, continuous range of color hues is used to indicate positive velocities and a second fixed, continuous range of color hues is used to indicate negative velocities. Typically, red/yellow hues show anatomical motion towards the transducer **10** and blue/green hues show motion away from the transducer **10**. The color hues **84** are illustrated in the color characteristic legend **85** shown in **FIG. 3**. The various cross-hatchings and lines in the color characteristic legend **85** of **FIG. 3** represent a continuous range of color hues. Going from the top of the color characteristic legend **85** to the bottom, the color hues transition from yellow to orange to red representing the positive velocity segment **81** of the color characteristic legend **85** and then violet to blue to green, representing the negative velocity segment **82** of the color characteristic legend **85**. However, the color hues **84** that make up the color characteristic legend **85** may be any continuous, semi-continuous, or discrete range of color hues that provide good discrimination between levels of the set of signal values **41**. The portions of the color characteristic legend **85** in which cross-hatched lines intersect represent a blending of color hues. Similarly, **FIG. 4** illustrates a color representation of strain rate imaging.

[**0036**] In step **110** of **FIG. 2**, ultrasound energy is received into transducer **10** and signals are received into front-end **20** in response to ultrasound waves **8** backscattered from the structure **105** over an operator-defined region of interest (ROI) **86** (see **FIG. 6**). The operator brings up a scaleable ROI **86** on monitor **90** through the user interface **60** to select a spatial or anatomical region to process such as the septum **104** of the heart (see **FIG. 6**). The ROI may be chosen to cover the entire displayed image **87** if desired. Such a selection of an ROI **86** forces the subsequent processing to segment, track, and time integrate a set of signal values **41** and display the resultant time integrated values in an image **87** for that specific region. The approach may, for example, be useful if the operator wants to provoke a good visualization of time integrated myocardial velocities in a specific region. In other similar embodiments, the ROI **86** may be selected automatically or as a combination of manual and automatic methods. For example, an algorithm **51** (see **FIG. 1**) for automatic identification of an ROI **86** may be designed and embedded in the host processor **50** to separate the myocardium from cavities. Well-known segmentation and thresholding techniques operating on the data of the set of signal values **41** may be used. The ROI **86** is automatically sized and positioned on display image **87** based on the results of the techniques.

[**0037**] In step **120** of **FIG. 2**, received signals **71** are sent from front-end **20** to Doppler processor **40** over digital bus **70**. Many sets of signal values **41**, such as mean velocity **42** or mean strain rate **43**, are generated from the received signals **71** over a segmented time period **45** and ROI **86** by Doppler processor **40**. The operator selects, through the user interface **60**, a desired time interval **45** to process, such as systole, which is a sub-interval of the cardiac cycle **46** (see **FIG. 7**). In **FIG. 8**, the time interval is designated by T_{start} and T_{end}. The time interval is determined from a timing signal **47** generated from a timing event source **65** (**FIG. 1**) and/or from characteristic signatures in the set of signal values **41**. An example of such a timing signal **47** is an ECG signal (see **FIG. 5**). Those skilled in ultrasound also know how to derive timing events from signals of other sources such as a phonocardiogram signal, a pressure wave signal, a pulse wave signal, or a respiratory signal. Ultrasound modalities such as spectrum Doppler or M-modes may also be used to obtain timing information.

[**0038**] T_{start} is typically selected by the operator as an offset from the R-event in the ECG signal. T_{end} is set such that the time interval covers a selected portion of the cardiac cycle such as systole. It is also possible to select a time period **45** corresponding to the complete cardiac cycle **46**. Another possibility is to limit the time period **45** to the systolic time period in order to display a color representation that is optimized for visualization of time integrated systolic parameters. Other sub-intervals of the cardiac cycle **46** may also be applied.

[**0039**] **FIG. 7** graphically illustrates typical sets of signal values **41** for velocity **42** and strain rate **43** which may be segmented into desired time periods based on signature characteristics of the sets. For reference, the profiles in **FIG. 7** are annotated with the times corresponding to: IVC= isovolumetric contraction, IVR=isovolumetric relaxation, E=early diastolic velocity, and A=late diastolic velocity. Caution must be taken in the selection of the time interval such that, for example, motion in the IVC or IVR period may be excluded from the analysis, if desired. An automatic function may be implemented to recognize and exclude the unwanted events from the time interval.

[**0040**] In other possible embodiments, the time interval may be selected automatically or as a combination of manual and automatic methods. For example, the time period **45** may be determined automatically with an algorithm **52** (see **FIG. 1**) embedded in host processor **50**. The algorithm **52** may use well-known techniques of analyzing the sets of signal values **41**, as shown in **FIG. 7**, looking for key signal signature characteristics and defining a time period **45** based on the characteristics, or similarly, analyzing the ECG signal **47**.

[0041] In step **130** of **FIG. 2**, the operator initiates, through user interface **60**, real time tracking of every sampled anatomical location **55** (**FIG. 7**) inside the selected ROI **86** over the selected time period **45** of the cardiac cycle **46**. The spatial set of signal values **41** are sent from Doppler processor **40** to host processor **50**, where a tracking function **147** is applied to the set of signal values **41**. **FIG. 10** is a flow chart of the tracking function **147**.

[0042] As an introduction to the tracking function **147**, a tracked velocity parameter profile **141** (V_1, V_2, . . . , V_n) (**FIG. 9**) for a given sampled anatomical location **55** in the myocardium **105**, is created over the time period T_{start} to T_{end} by converting the spatial set of velocity values **42** into a motion parameter profile **151** in time using host processor **50** by computing the series of time integrals (S_1, S_2, . . . ,S_n) where:

$$S_i=T*(V_1+V_2+. . . +V_i) \quad \text{[Equation 1]}$$

[0043] and where T is the time delay between two consecutive velocity measurements (T is typically based on the frame rate of the imaging mode). S_i (motion value) is then the longitudinal distance in mm (from reference time T_{start} location) that a sample of tissue in the myocardium has moved at time segment T_i, thus allowing the isolated tissue sample to be tracked longitudinally (along the ultrasound beam) over the time interval T_{start} to T_{end} by host processor **50**. The tracking function estimates the new anatomical location of the tracked sample tissue after every time segment T_i and determines tracked velocities (or other estimated parameters) at the new anatomical locations. The tracking is done for each sampled anatomical location **55** in the selected ROI **86**.

[0044] The upper part of **FIG. 9** shows a resultant tracked velocity parameter profile **141** of a sampled anatomical location **55** in the image as a function of time for a complete cardiac cycle **46**. The lower part of **FIG. 9** shows the corresponding resultant longitudinal motion parameter profile **151** (integrated velocity profile, S_1, S_2, . . . , S_n) of the same sampled anatomical location in the image. Motion along the ultrasound beam may be accurately tracked with the technique allowing the appropriate velocity parameter profiles (or other estimated parameter profiles) to be generated for the corresponding anatomical locations. The tracked estimated parameter profile **141** for each anatomical location is stored in the memory of host processor **50** as a sampled array of estimated parameter values. As a result, the stored parameter profile history corresponds to each anatomical location, instead of just a spatial location in the image.

[0045] Two-dimensional velocity estimation is necessary for accurate tracking when a substantial part of the motion of the structure is orthogonal to the beam. Other tracking techniques may be employed as well.

[0046] As an alternative to tracking, spatial estimated parameter profiles may be constructed by the host processor **50** from the set of signal values and correlated to fixed spatial locations in the image instead of to anatomical locations. Subsequent time integration will then be performed at fixed spatial locations over the time period **45**.

[0047] The specific steps of the preferred tracking function **147** are now described for a given sampled anatomical location **55** in the ROI **86**. A spatial set of mean velocity values **42** is estimated in step **120** of **FIG. 2** so that the motion values S_i may be calculated for tracking. The mean velocity values are generated by Doppler processor **40** in a well-known manner.

[0048] Referring to **FIG. 10**, in step **142** of tracking function **147**, processor **50** selects V_i for a given anatomical location in the image from a spatial set of velocity values **42** in the ROI **86** corresponding to time interval T_i where i=1 (T_1 is T_{start}).

[0049] In step **143** of tracking function **147**, processor **50** computes the motion value S_i for the given anatomical location in the ROI, as

$$S_i=T*(V_1+V_2+. . . +V_i) \quad \text{[Equation 1]}$$

[0050] (Note that for i=1, $S_1=T*V_1$)

[0051] In step **144** of tracking function **147**, processor **50** stores V_i in tracked velocity parameter profile array **141** and S_i is stored in motion parameter profile array **151** along with the current spatial position of the anatomical location. Other estimated parameters, such as strain rate, corresponding to the tracked anatomical location may be stored in respective tracked profile arrays as well.

[0052] In step **145** of tracking function **147**, i is incremented by one (corresponding to the next sample time, T seconds later) and the next V_i is selected from the spatial set of velocity values **42** based on the motion parameter S_i previously computed and the previous spatial position of the anatomical location (S_i represents the longitudinal spatial movement in mm of the anatomical location over time interval $T_i=i*T$).

[0053] In step **146** of tracking function **147**, the function checks to see if T_{end} has been exceeded. If T_{end} has not been exceeded, the function proceeds back to step **143** and computes the next motion parameter value S_i in the series using Equation 1. The iterative process is followed until the full arrays of tracked velocity parameter profiles **141**, motion parameter profiles **151**, and any other desired estimated parameter profile have been created and stored over the complete time interval T_{start} to T_{end}.

[0054] The tracking function **147** is performed simultaneously for each anatomical location in the ROI **86**.

[0055] **FIG. 11** illustrates the function of generating the displays of time integrated displacement parameters for the imaging modes of TVI and SRI. When velocity estimates are integrated over time, the resultant displacement parameter value **152** (shaded areas of **FIG. 8**) is a distance moved **153** (**FIG. 11**) in units of length such as millimeters (mm). A resultant display of time integrated velocity is shown in the upper right of **FIG. 11**. The display represents displacement of the cardiac tissue over the integrated time period.

[0056] Strain rate SR, in units of 1/seconds, is computed as radial gradients of the velocity estimates. Strain rate SR is a spatial derivation of velocity and is the rate at which tissue velocity is changing over a radial distance. When the gradient of the tissue velocity is computed along the ultrasound beam, a strain rate image will be obtained as shown in the lower left of **FIG. 11**. The computation may be expressed as:

$$SR=\Delta V/\Delta x \quad \text{[Equation 2]}$$

[0057] where SR is strain rate and Δ V is the change in velocity over the longitudinal distance Δ x (longitudinal tissue segment). SR is typically color encoded at Δ x/2, the center of the tissue segment.

[0058] When strain rate is integrated over time, the resultant displacement parameter value **152** is a deformation **154** (**FIG. 11**) that is unitless but may be expressed as a total deformation of the tissue in percentage as shown in the lower right of **FIG. 11** resulting in a measure of the deformation **154** of a segment of tissue around Δ x/2 which is the center of the tissue segment Δ x. If the time integration is performed from T_{start} to T_{end}, the value of the time integral **152** is a measure of the relative deformation **154** of the tissue segment over the time interval. If the time integration starts at, for example, the beginning of systole (contraction phase of the heart cycle), and the value is calculated to be 0.5 at the end of systole, then the tissue segment Δ x surrounding the location Δ x/2 has a deformation of 50%. The deformation **154** is used to color encode the location Δ x/2 and is calculated based on samples in a neighborhood around the location continuous, Δ x/2 for a given tissue segment Δ x.

[0059] In step **140** of **FIG. 2**, the stored, tracked estimated parameter profiles **141** (e.g. longitudinal mean velocity or strain rate profiles) for each sampled anatomical location **55** are integrated over the time interval T_{start} to T_{end} by the host processor **50** by a time integration function in host processor **50** which approximates the true time integral by summing tracked values as follows:

$$S_{int}=T^{*}(Q_{start}+Q2+Q3+\ldots+Q_{end}) \qquad \text{[Equation 3]}$$

[0060] is the time integrated value **152** (displacement parameter value), Q_{start} is the first value in the tracked movement parameter profile **141** (corresponding to T_{start}) and Q_{end} is the last (corresponding to T_{end}) For tissue velocity imaging, Q is V and for tissue strain rate imaging, Q is SR. Each shaded area **152** under the profiles in **FIG. 8** represent a displacement parameter value calculated by integrating velocity values **42** over the time interval T_{start} to T_{end}.

[0061] The time integration function is performed simultaneously for each anatomical location in the ROI **86**.

[0062] Care should be taken by the operator to adjust the Nyquist frequency of the imaging mode such that aliasing does not occur. With aliasing present in the data, erroneous results occur. Alternatively, well known automatic aliasing correction techniques may be employed.

[0063] In step **150** of **FIG. 2**, the time integrated displacement parameter value S_{int} for each tracked anatomical location is used to color encode the associated location in the image in display processor **80**. The displacement parameter values **152** are sent from host processor **50** to display processor **80** for image formatting and color encoding. The time integrated values S_{int} may either be color encoded with the same color encoding (color mapping table) as the underlying TVI or SRI imaging mode, or a dedicated color encoding may be devised for the time integrated display. Clinical work on time integrated velocities shows that it is advantageous to design a color encoding such that quantitative values may be inferred directly from the color encoding.

[0064] **FIG. 8** illustrates a display of color-encoded time integrated velocities (i.e. displacement parameter values) of a myocardial segment of the heart in a displayed color representation **95** on monitor **90** (**FIG. 1**) using a predefined, discrete color mapping table where N discrete colors are used to visualize the time integrated velocities. In the example, seven discrete color hues are used to separate between time integrated velocities: 0-2 mm, 2-4 mm, 4-6 mm and to >12 mm in color legend areas **85**A-**85**G respectively (see color legend of **FIG. 8**). The number of discrete colors may be increased over the scale of the color legend in order to get a finer separation of time integrated values. The color hues are typically represented in memory as red, green, blue (RGB) values as shown in **FIG. 12**. The RGB values constitute the color characteristic signals **83**. The RGB values may be represented as normalized values between 0 and 1, as shown in **FIG. 12**. Therefore, to represent a perfectly red hue, the RGB values are (1 0 0). For a perfectly green hue, the RGB values are (0 1 0), and for blue (0 0 1). An RGB combination of (1 1 1) yields a perfectly white hue and an RGB combination of (0 0 0) yields a perfectly black hue. Any other color hue may be represented by various combinations of RGB values. For example, if an RGB value is (0.5 0.8 0.3), a combination of unequal parts of red, green, and blue hues each with a different weighting, the result is some new color hue.

[0065] As an alternative, time integration may be performed after each new tracked element in the tracked movement parameter profile array is added or after each new spatial element is added to the spatial movement parameter profile, instead of waiting until T_{end} to perform the integration allowing a constant update of the displayed time integrated values within the time interval T_{start} to T_{end}.

[0066] The time integrated value corresponding to the cutoff for the color encoding of the highest time integration value may be preset in order to relate the time integration values to normal physiological values. Typically, a normal physiological value may be used for the preset. The setting will depend on the image view and the stress level in a stress echo exam. If for instance the normal basal peak velocity integral is selected, one can determine whether a patient has normal longitudinal function at the given stress level simply by checking whether the color corresponding to the highest velocity integral index appears in the basal segment. Different anatomical segments may be addressed in a similar manner. A reduction in longitudinal function may be quantified by evaluating the percentage of the normal velocity integral range that is actually observed. The assessment may also indirectly be an assessment of global function because of the strong correlation between Ejection Fraction and systolic, longitudinal motion of the mitral annulus.

[0067] As another possible embodiment, more than one displacement parameter value **152** may be extracted from the same cardiac cycle and combined for display. An example is the computation and display of ratio images where the process described herein for determination of time integrated values is performed over two time periods and the ratio between the two time integrated values is used to color encode the spatial or tracked anatomical locations.

[0068] Referring to **FIG. 13**, the displacement parameter value is a ratio value **163**. The ratio value **163** is derived from a set of displacement parameter signals **160** comprising a first parameter signal **161** representing a first displacement **1611** of the moving structure **105** over a first time period **48** and a second parameter signal **162** representing a second displacement **1621** of the moving structure **105** over a second time period **49**. The ratio value **163** is the ratio of the time integrated value **1611** (first displacement) of the first

parameter signal **161** and the time integrated value **1621** (second displacement) of the second parameter signal **162**. The ratio value **163** is then color encoded and displayed for each sampled anatomical location **55** in the ROI **86**. For example, the first time period may correspond to systole and the second time period may correspond to IVR allowing quantification and displaying of IVR activity relative to systolic excursions.

[**0069**] Images of ratio values remove the angle dependence of, for example, tissue velocity imaging because the unknown cosine modulation caused by the angle of incidence is the same in both measurements. Ratios of other combinations may be calculated and displayed as well. For example, it may be useful to compute ratios between time integrated values and peak signal values for a given time period. The ratio contains information related to acceleration in the selected time period.

[**0070**] The embodied method may be applied to any imaging mode of the ultrasound machine **5** for moving structure, for any estimated parameter (e.g. velocity, strain rate, power, amplitude, etc.).

[**0071**] In summary, certain embodiments of the present invention afford an approach to more easily visualize tissue displacement parameter information, such as time integrated velocity and time integrated strain rate, in a two-dimensional ultrasound image.

[**0072**] While the invention has been described with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed, but that the invention will include all embodiments failing within the scope of the appended claims.

1. In an ultrasound machine for generating an image responsive to moving structure within a region of interest of a subject, apparatus for displaying a color characteristic representing displacement of the moving structure comprising:

a front-end arranged to transmit ultrasound waves into the structure and to generate received signals in response to ultrasound waves backscattered from the structure in the region of interest over a time period;

a processor responsive to the received signals to generate a parameter value representing displacement of the moving structure during the time period and responsive to the parameter value to generate a color characteristic signal representative of the displacement; and

a display arranged to display a color characteristic representative of the displacement of the moving structure in response to the color characteristic signal.

2. The apparatus of claim 1 wherein the moving structure comprises cardiac tissue.

3. The apparatus of claim 1 wherein the displacement represents one of distance moved by the moving structure and deformation of the moving structure.

4. The apparatus of claim 1 wherein the color characteristic comprises hue.

5. The apparatus of claim 1 wherein the processor generates the parameter value by summing a set of signal values representing velocities of the moving structure over the time period.

6. The apparatus of claim 1 wherein the processor generates the parameter value by summing a set of signal values representing strain rates of the moving structure over the time period.

7. The apparatus of claim 1 wherein the time period comprises at least a portion of a cardiac cycle selectable by a user of the machine including at least one of systole, diastole, IVC, IVR, E-wave, and A-wave.

8. The apparatus of claim 7 wherein the portion of the cardiac cycle is selectable from at least one of the set of signal values and a timing event signal comprising at least one of an ECG signal, a phonocardiogram signal, a pressure wave signal, a pulse wave signal, and a respiratory signal.

9. The apparatus of claim 1 wherein the parameter value represents displacement of a sampled anatomical location of the moving structure within the region of interest.

10. The apparatus of claim 1 wherein the parameter value is derived from a set of parameter signals, wherein the set of parameter signals comprises a first parameter signal representing a first displacement of the moving structure and a second parameter signal representing a second displacement of the moving structure, and wherein the color characteristic signal represents the ratio of the first displacement and the second displacement.

11. In an ultrasound machine for generating an image responsive to moving structure within a region of interest of a subject, a method of displaying a color characteristic representing displacement of the moving structure comprising:

transmitting ultrasound waves into the structure;

generating received signals in response to ultrasound waves backscattered from the structure in the region of interest over a time period;

generating a parameter value representing displacement of the moving structure during the time period in response to the received signals;

generating a color characteristic signal representative of the displacement in response to the parameter value; and

displaying a color characteristic representative of the displacement of the moving structure in response to the color characteristic signal.

12. The method claim 11 wherein the moving structure comprises cardiac tissue.

13. The method of claim 11 wherein the displacement represents one of distance moved by the moving structure and deformation of the moving structure.

14. The method of claim 11 wherein the color characteristic comprises hue.

15. The method of claim 11 wherein said generating a parameter value comprises summing a set of signal values representing velocities of the moving structure over the time period.

16. The method of claim 11 wherein said generating a parameter value comprises summing a set of signal values representing strain rates of the moving structure over the time period.

17. The method of claim 11 wherein the time period comprises at least a portion of a cardiac cycle selectable by a user of the machine.

18. The method of claim 17 wherein the portion of the cardiac cycle is selectable from at least one of the set of signal values and a timing event signal comprising at least one of an ECG signal, a phonocardiogram signal, a pressure wave signal, a pulse wave signal, and a respiratory signal.

19. The method of claim 11 wherein the parameter value represents displacement of a sampled anatomical location of the moving structure within the region of interest.

20. The method of claim 11 wherein the parameter value is derived from a set of parameter signals, wherein the set of parameter signals comprises a first parameter signal representing a first displacement of the moving structure and a second parameter signal representing a second displacement of the moving structure, and wherein the color characteristic signal represents the ratio of the first displacement and the second displacement.

* * * * *

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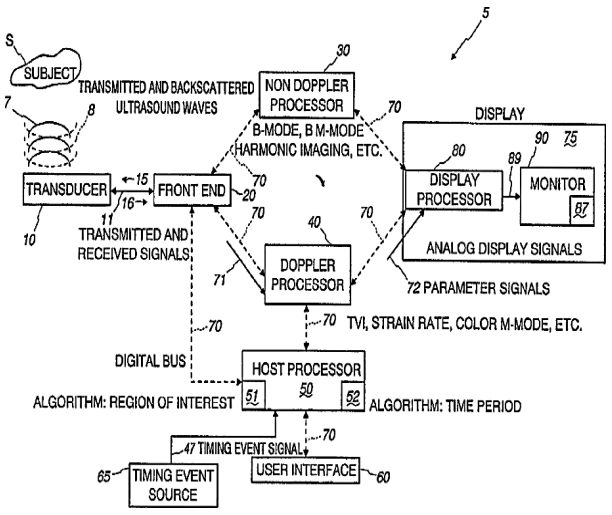
摘要(译)

一种超声波机器，其产生移动结构的颜色表示，例如感兴趣区域内的心脏壁组织，并显示在监视器上。通过显示与结构的一组信号值相关的至少一个颜色特性（例如速度或应变率）来生成颜色表示。该组信号值的相关特征通过包括前端的装置映射到颜色特性，该前端响应于反向散射的超声波产生接收信号。多普勒处理器生成表示移动结构的空间值集的一组信号值。主处理器包含跟踪功能和时间积分功能，以在对应于感兴趣区域内的采样解剖位置的时间段内生成跟踪的运动参数轮廓和位移参数值。然后将位移参数值映射到颜色特征信号。显示处理器将颜色特征信号的值映射到表示移动结构的位移参数值，以在监视器上显示颜色表示。