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(54) **THIRD HEART SOUND ACTIVITY INDEX  
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**2562/0219** (2013.01); **A61B 2562/0204**  
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May 23, 2014, now Pat. No. 9,668,713, which is a  
continuation of application No. 13/933,937, filed on  
Jul. 2, 2013, now Pat. No. 8,840,563, which is a  
continuation of application No. 13/540,092, filed on  
Jul. 2, 2012, now Pat. No. 8,500,650, which is a  
continuation of application No. 11/465,878, filed on  
Aug. 21, 2006, now Pat. No. 8,211,033, which is a  
division of application No. 10/746,874, filed on Dec.  
24, 2003, now Pat. No. 7,115,096.

(57)

**ABSTRACT**

A cardiac rhythm management system provides for the trending of a third heart sound (S3) index. The S3 index is a ratio, or an estimate of the ratio, of the number of S3 beats to the number of all heart beats, where the S3 beats are each a heart beat during which an occurrence of S3 is detected. An implantable sensor such as an accelerometer or a microphone senses an acoustic signal indicative heart sounds including S3. An S3 detector detects occurrences of S3 from the acoustic signal. A heart sound processing system trends the S3 index on a periodic basis to allow continuous monitoring of the S3 activity level, which is indicative of conditions related to heart failure.

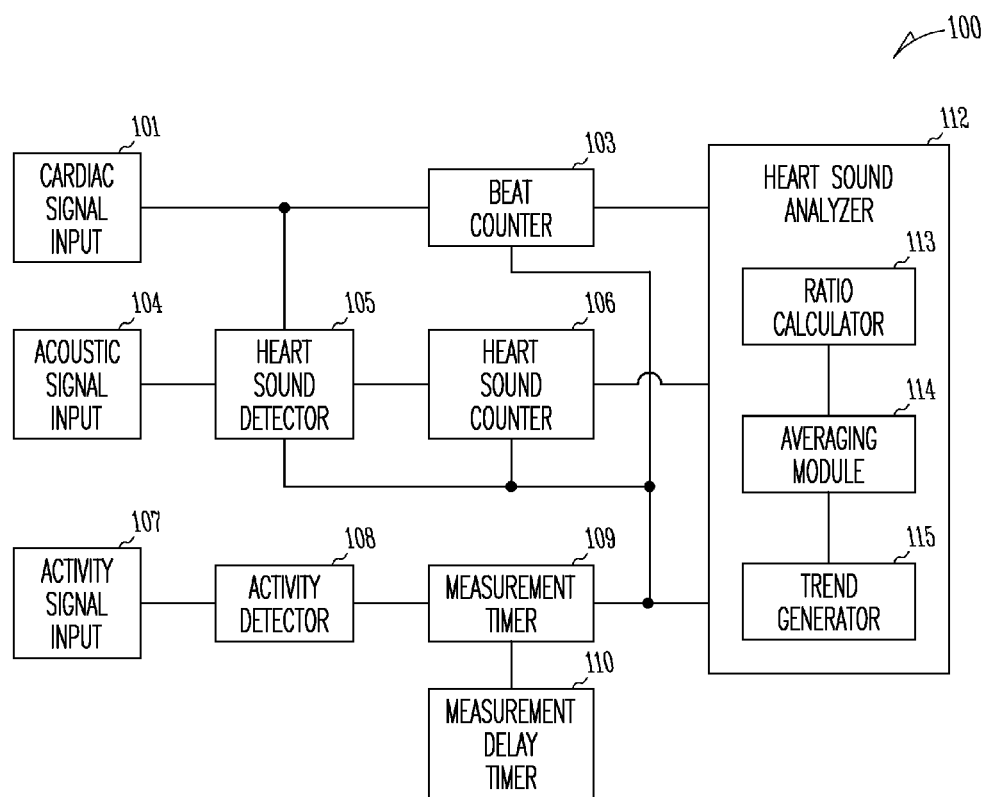


Fig. 1

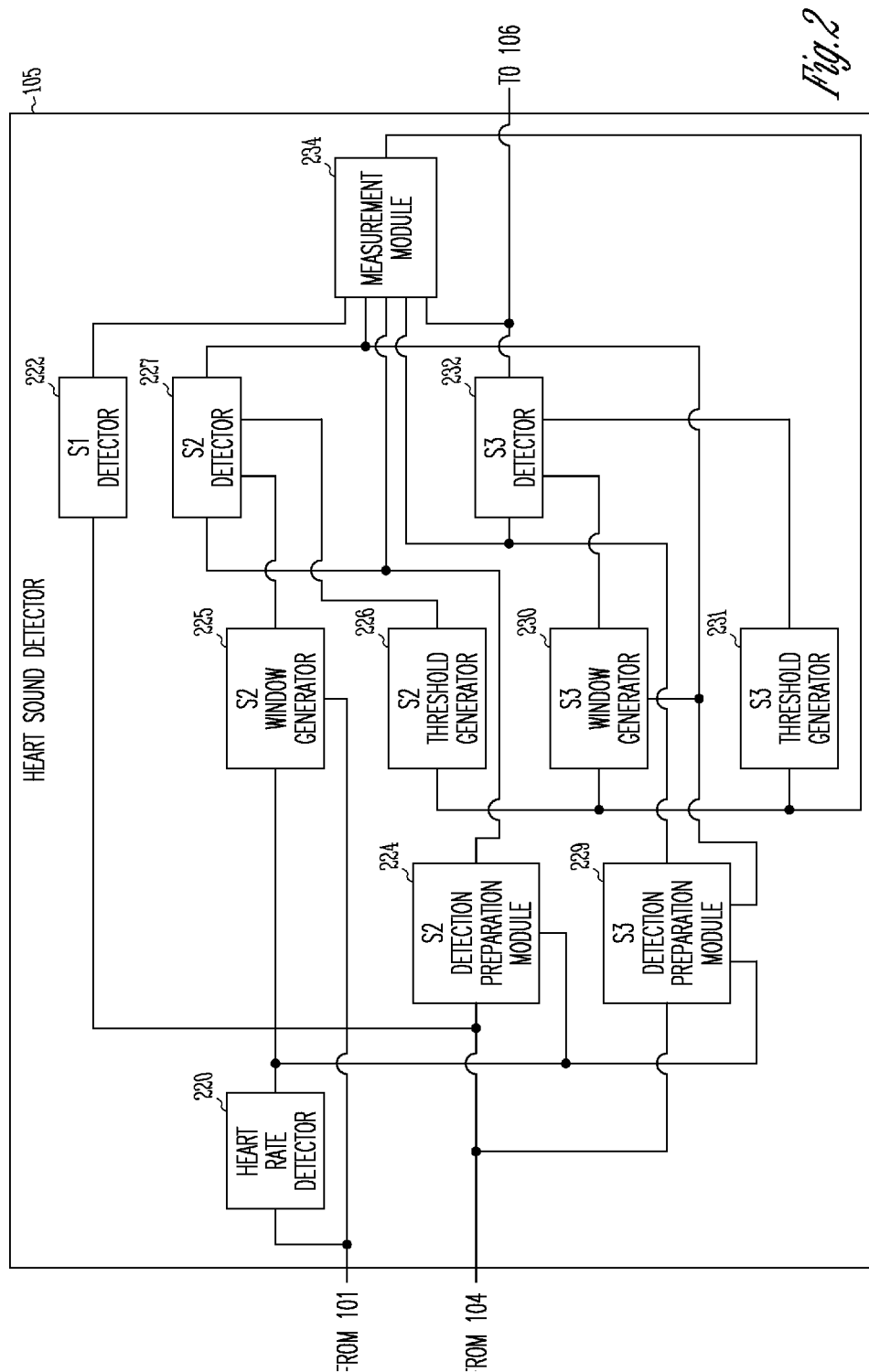


Fig. 2

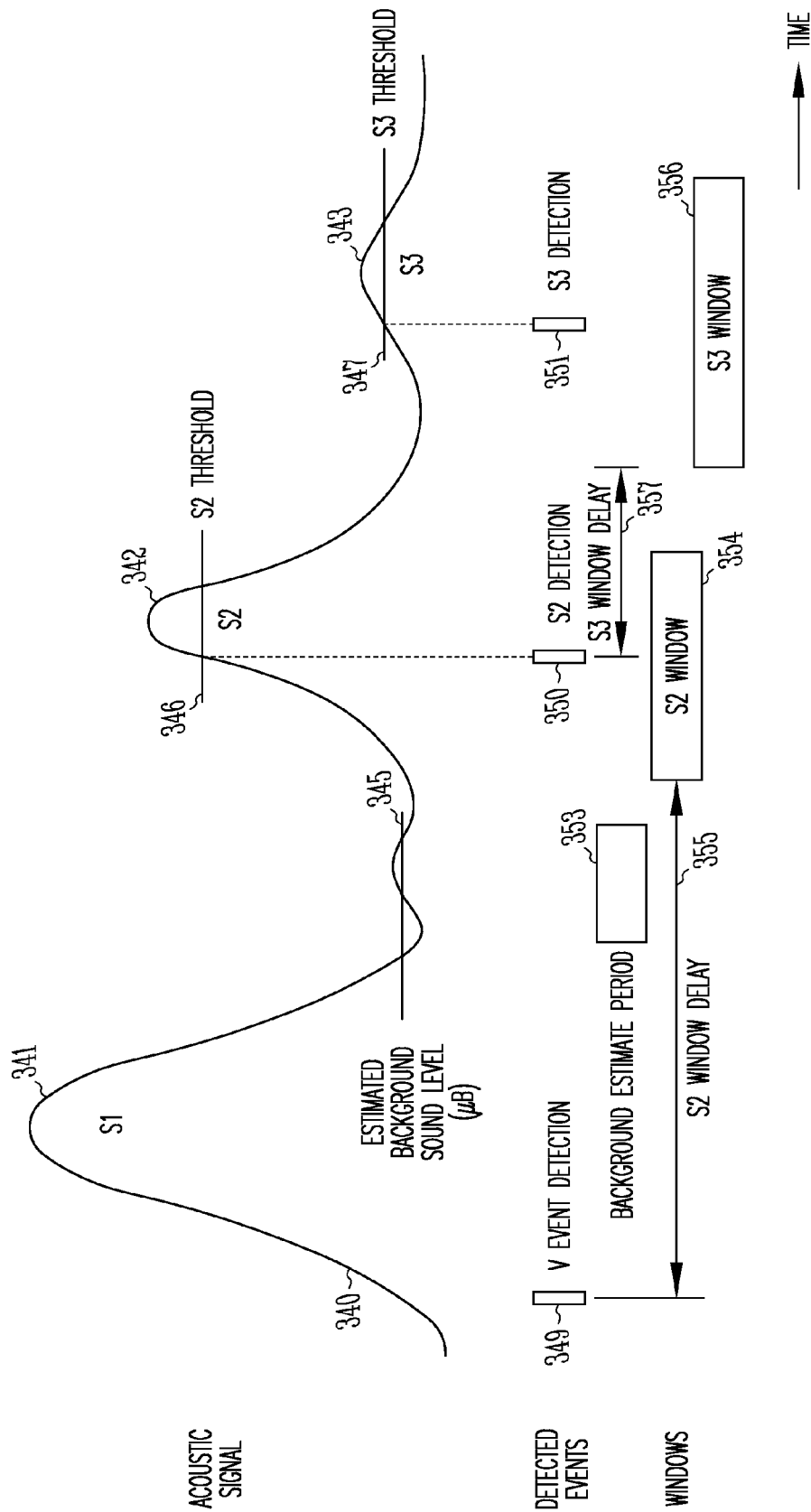


Fig. 3

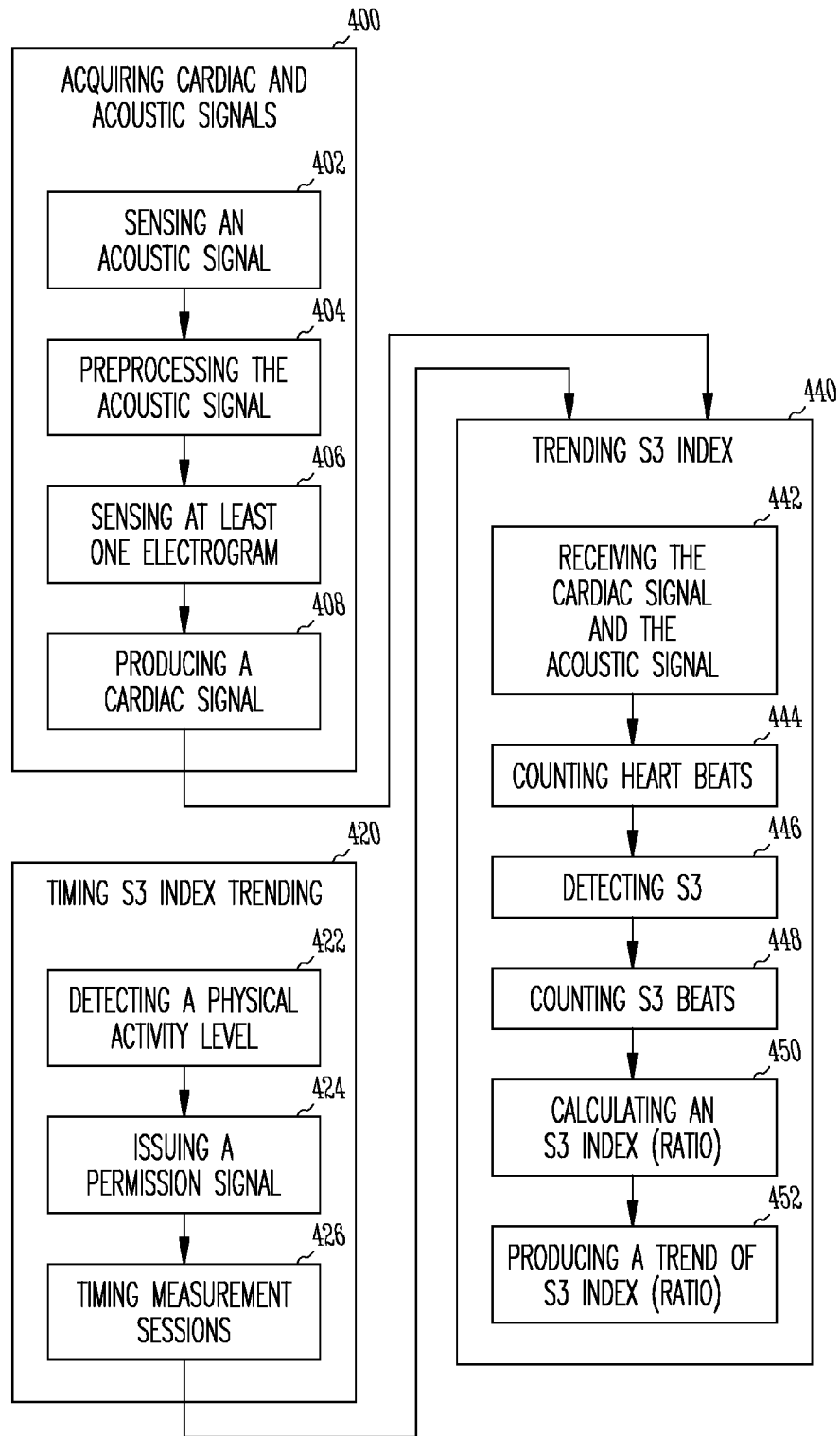


Fig. 4

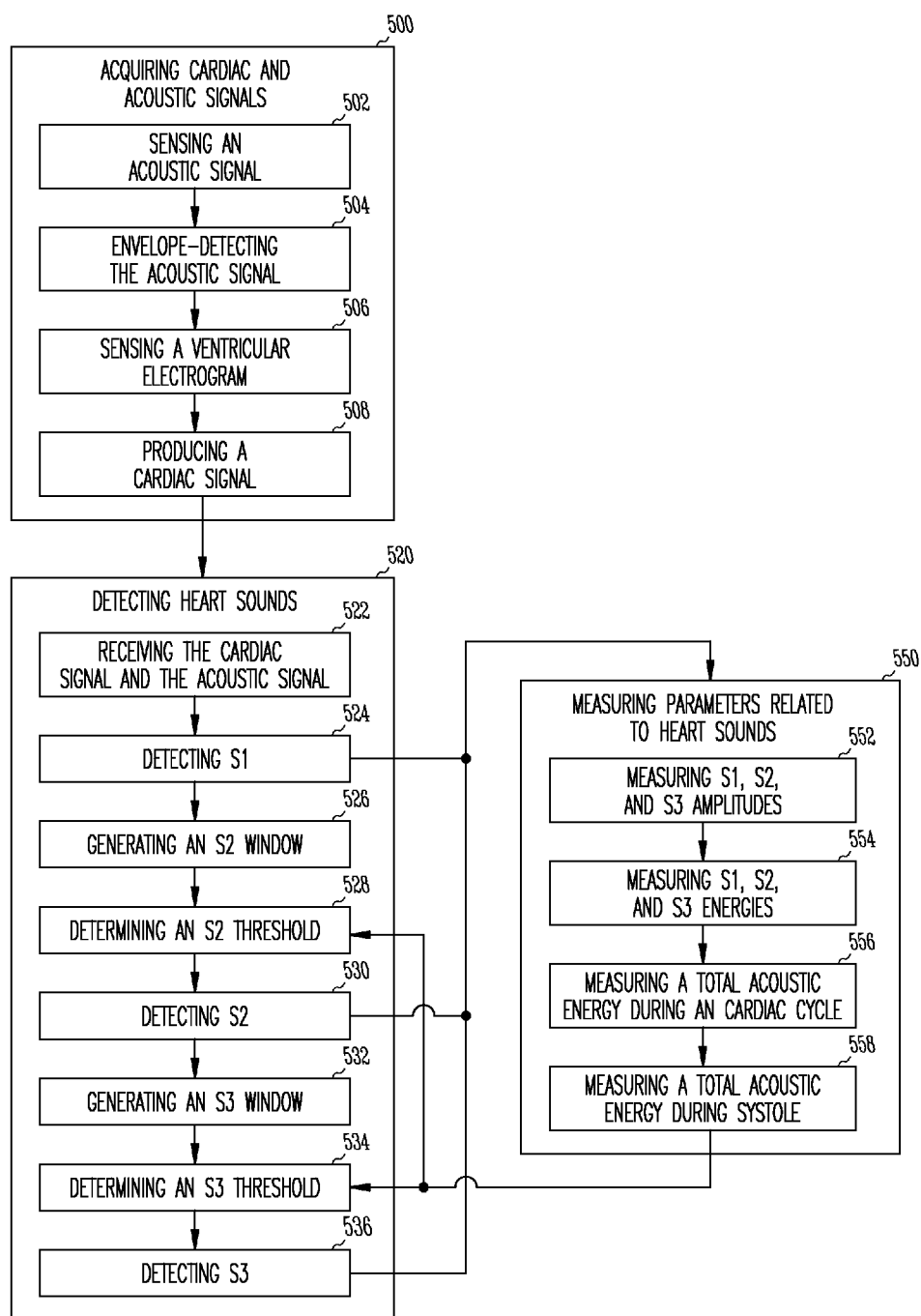


Fig. 5

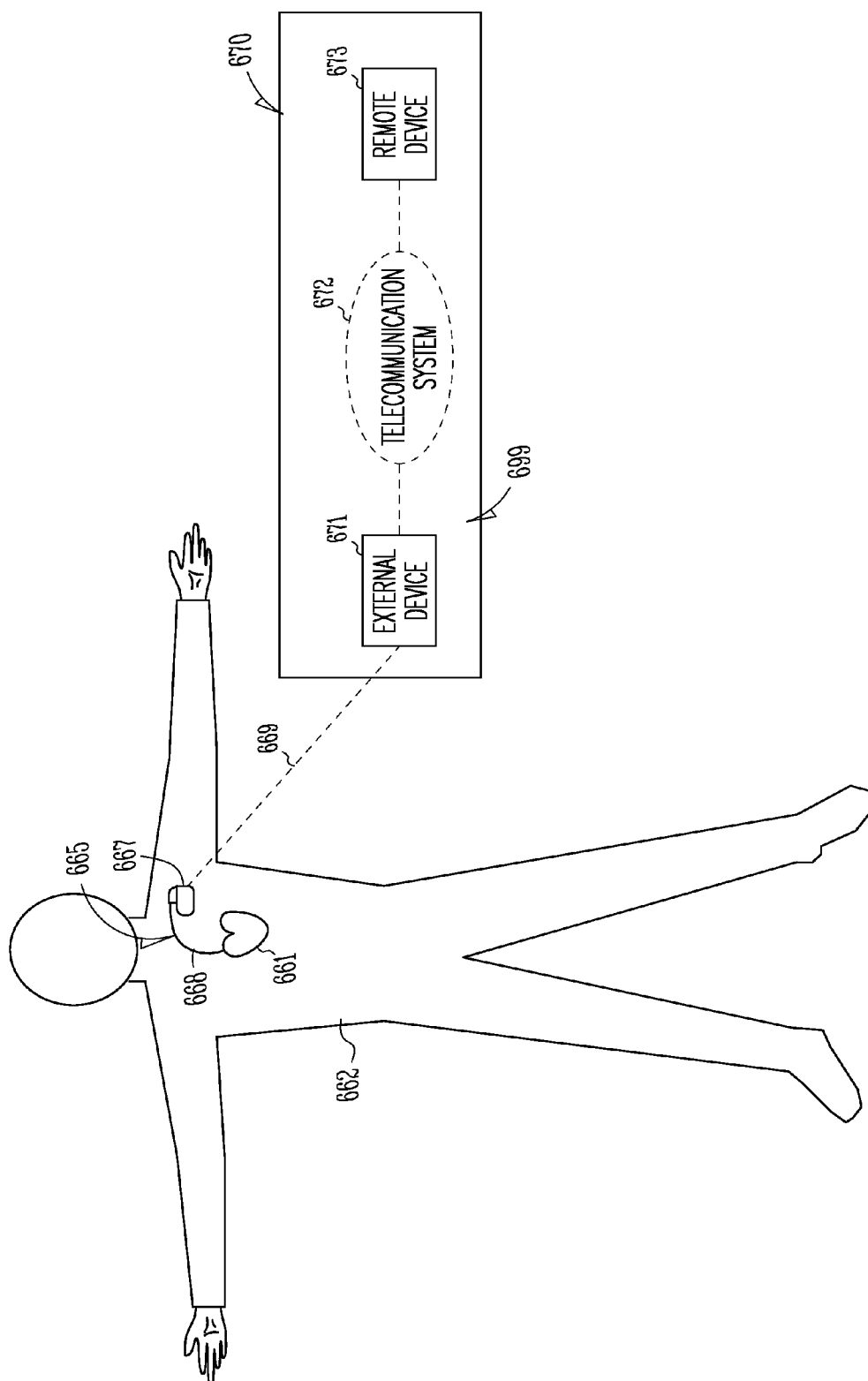


Fig. 6

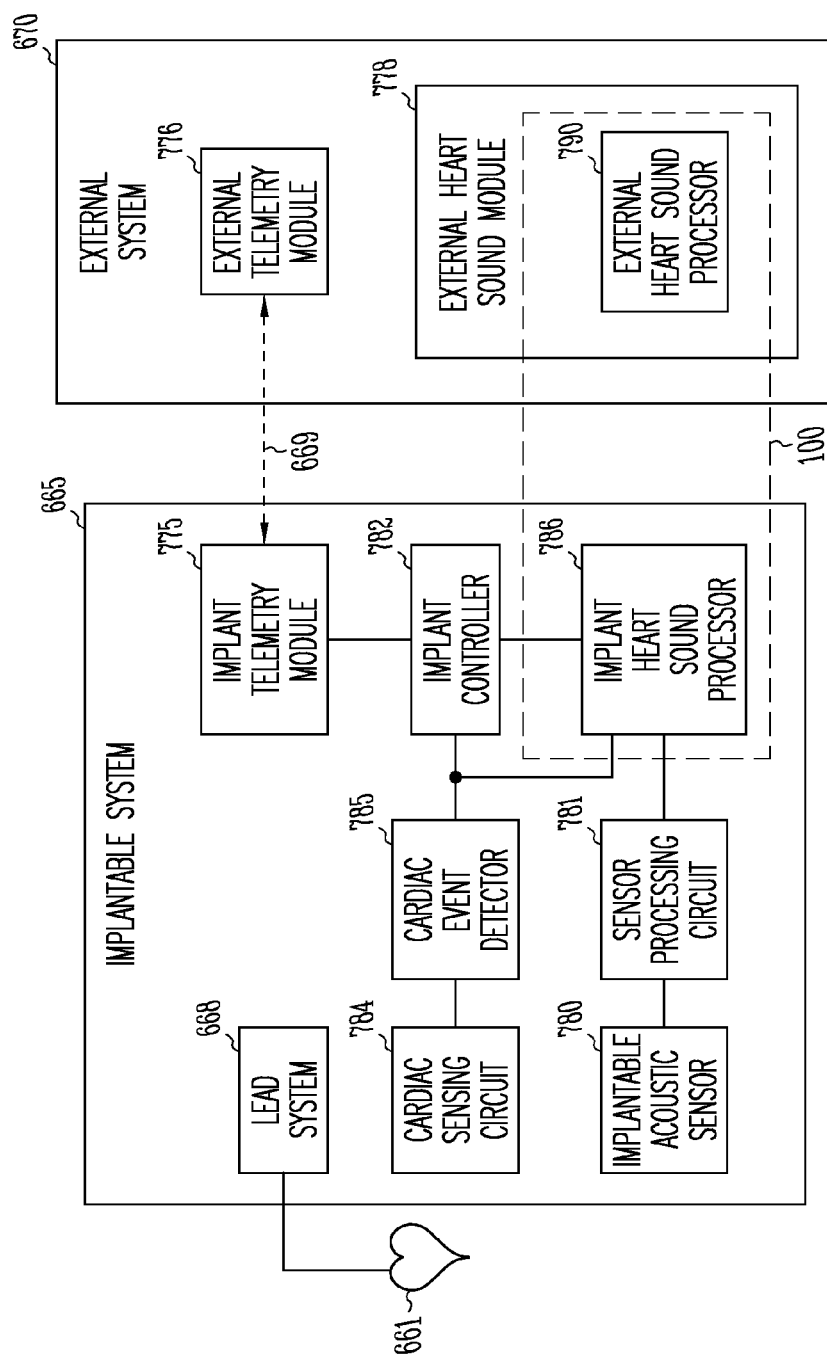


Fig. 7

### THIRD HEART SOUND ACTIVITY INDEX FOR HEART FAILURE MONITORING

#### CLAIM OF PRIORITY

[0001] This application is a continuation of U.S. application Ser. No. 14/286,314, filed on May 23, 2014, which is a continuation of U.S. application Ser. No. 13/933,937, filed on Jul. 2, 2013, now issued as U.S. Pat. No. 8,840,563, which is a continuation of U.S. application Ser. No. 13/540,092, filed on Jul. 2, 2012, now issued as U.S. Pat. No. 8,500,650, which is a continuation of U.S. application Ser. No. 11/465,878, filed on Aug. 21, 2006, now issued as U.S. Pat. No. 8,211,033, which is a divisional of U.S. application Ser. No. 10/746,874, filed on Dec. 24, 2003, now issued as U.S. Pat. No. 7,115,096, all of which are incorporated herein by reference.

#### CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application is also related to co-pending, commonly assigned U.S. patent application Ser. No. 10/746,853, entitled "METHOD AND APPARATUS FOR THIRD HEART SOUND DETECTION," filed on Dec. 24, 2003, now issued as U.S. Pat. No. 7,431,699, U.S. patent application Ser. No. 10/334,694, entitled "METHOD AND APPARATUS FOR MONITORING OF DIASTOLIC HEMODYNAMICS," filed Dec. 30, 2002, now issued as U.S. Pat. No. 7,972,275, and U.S. patent application Ser. No. 10/307,896, "PHONOCARDIOGRAPHIC IMAGE-BASED ATRIOVENTRICULAR DELAY OPTIMIZATION," filed Dec. 12, 2002, now issued as U.S. Pat. No. 7,123,962, all assigned to Cardiac Pacemakers, Inc., which are hereby incorporated by reference in their entirety.

#### TECHNICAL FIELD

[0003] This document relates generally to cardiac rhythm management systems and particularly, but not by way of limitation, to such a system sensing and analyzing heart sounds for monitoring, diagnosis, and therapy control.

#### BACKGROUND

[0004] The heart is the center of a person's circulatory system. It includes a complex electro-mechanical system performing two major pumping functions. The left portions of the heart draw oxygenated blood from the lungs and pump it to the organs of the body to provide the organs with their metabolic needs for oxygen. The right portions of the heart draw deoxygenated blood from the organs and pump it into the lungs where the blood gets oxygenated. These mechanical pumping functions are accomplished by contractions of the myocardium (heart muscles). In a normal heart, the sinoatrial (SA) node, the heart's natural pacemaker, generates electrical impulses, called action potentials, that propagate through an electrical conduction system to various regions of the heart to excite myocardial tissues in these regions. Coordinated delays in the propagations of the action potentials in a normal electrical conduction system cause the muscles in various regions of the heart to contract in synchrony such that the pumping functions are performed efficiently. The normal pumping functions of the heart, or the normal hemodynamic performance, require a normal electrical system to generate the action potentials and deliver them to designated portions of the myocardium with proper

timing, a normal myocardium capable of contracting with sufficient strength, and a normal electro-mechanical association such that all regions of the heart are excitable by the action potentials.

[0005] Electrocardiography (ECG) is known to indicate the functions of the electrical system by allowing monitoring of the action potentials at various portions of the heart. Heart sounds, or generally energies resulted from the heart's mechanical vibrations, indicate the heart's mechanical activities. Measurements performed with simultaneously recorded ECG and heart sounds provide for quantitative indications of the electro-mechanical association.

[0006] One type of heart sound, known as the third heart sound, or S3, is known as an indication of heart failure. A heart failure patient suffers from an abnormal electrical conduction system with excessive conduction delays and deteriorated heart muscles that result in asynchronous and weak heart contraction, and hence, reduced pumping efficiency, or poor hemodynamic performance. While the ECG of a heart failure patient may show excessive delays and/or blockages in portions of the electrical conduction system, S3 indicates his or her heart's abnormal mechanical functions. For example, an increase in S3 activity is known to be an indication of elevated filing pressures, which may result in a state of decompensated heart failure. Additionally, S3 amplitude is also related to filing pressures of the left ventricle during diastole. The pitch, or fundamental frequency, of S3 is related to ventricular stiffness and dimension. Chronic changes in S3 amplitude are correlated to left ventricular chamber stiffness and degree of restrictive filling. Such parameters indicate abnormal cardiac conditions, including degrees of severity, and need of appropriate therapies. For these and other reasons, there is a need for a system providing for S3 detection and analysis.

#### SUMMARY

[0007] A cardiac rhythm management system provides for the trending of a third heart sound (S3) index. The S3 index is a ratio, or an estimate of the ratio, of the number of S3 beats to the number of all heart beats, where the S3 beats are each a heart beat during which an occurrence of S3 is detected. An implantable sensor such as an accelerometer or a microphone senses an acoustic signal indicative heart sounds including S3. An S3 detector detects occurrences of S3 from the acoustic signal. A heart sound processing system trends the S3 index on a periodic basis to allow continuous monitoring of the S3 activity level, which is indicative of conditions related to heart failure.

[0008] In one embodiment, a heart sound processing system includes a cardiac signal input, a beat counter, an acoustic signal input, a heart sound detector, a heart sound counter, and a heart sound analyzer. The cardiac signal input receives a cardiac signal indicative of heart beats. The beat counter counts the heart beats. The acoustic signal input receives an acoustic signal indicative of at least S3. The heart sound detector detects S3. The heart sound counter counts S3 beats each being a heart beat during which one of S3 is detected. The heart sound analyzer includes a ratio calculator that calculates an S3 index, which is a ratio of a number of the S3 beats counted during a predetermined time period to the number of the heart beats counted during the predetermined time period.

[0009] In one embodiment, a cardiac rhythm management system includes an implantable system and an external

system communicatively coupled to the implantable medical device. The implantable system includes an implantable acoustic sensor, an implant heart sound processor, and an implant telemetry module. The implantable acoustic sensor senses an acoustic signal indicative of at least S3. The implant heart sound processor processes the acoustic signal. The implant telemetry module transmits the processed acoustic signal. The external system includes an external telemetry module and an external heart sound module. The external telemetry module receives the processed acoustic signal. The external heart sound module generates a trend of the S3 index.

**[0010]** In one embodiment, a heart sound processing method provides for the S3 index trending. A cardiac signal indicative of cardiac events and an acoustic signal indicative of at least S3 are received. The cardiac events are detected from the cardiac signal. The heart beats are counted based on the cardiac events. S3 is detected from the acoustic signal. S3 beats, which are each a heart beat during which an occurrence of S3 is detected, are counted. The S3 index is trended, based on the number of the S3 beats counted during a predetermined time period and the number of the heart beats counted during that predetermined time period.

**[0011]** This Summary is an overview of some of the teachings of the present application and not intended to be an exclusive or exhaustive treatment of the present subject matter. Further details about the present subject matter are found in the detailed description and appended claims. Other aspects of the invention will be apparent to persons skilled in the art upon reading and understanding the following detailed description and viewing the drawings that form a part thereof, each of which are not to be taken in a limiting sense. The scope of the present invention is defined by the appended claims and their equivalents.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0012]** In the drawings, which are not necessarily drawn to scale, like numerals describe similar components throughout the several views. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

**[0013]** FIG. 1 is a block diagram illustrating an embodiment of a heart sound processing system for trending an S3 index.

**[0014]** FIG. 2 is a block diagram illustrating an embodiment of a heart sound detector.

**[0015]** FIG. 3 is an illustration of an embodiment of a method for detecting selected heart sounds.

**[0016]** FIG. 4 is a flow chart illustrating an embodiment of a method for trending the S3 index using the system of FIG. 1.

**[0017]** FIG. 5 is a flow chart illustrating an embodiment of a method for detecting S3 using the heart sound detector of FIG. 2.

**[0018]** FIG. 6 is an illustration of an embodiment of portions of a cardiac rhythm management system incorporating the heart sound processing system of FIG. 1, and portions of an environment in which it is used.

**[0019]** FIG. 7 is a block diagram illustrating a specific embodiment of portions of the cardiac rhythm management system of FIG. 6.

#### DETAILED DESCRIPTION

**[0020]** In the following detailed description, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that the embodiments may be combined, or that other embodiments may be utilized and that structural, logical and electrical changes may be made without departing from the spirit and scope of the present invention. The following detailed description provides examples, and the scope of the present invention is defined by the appended claims and their equivalents.

**[0021]** It should be noted that references to “an”, “one”, or “various” embodiments in this disclosure are not necessarily to the same embodiment, and such references contemplate more than one embodiment.

**[0022]** This document discusses, among other things, a cardiac rhythm management system monitoring and analyzing heart sounds, particularly the third heart sounds (S3), that are indicative of a heart's mechanical events related to the heart's pumping functions and hemodynamic performance to allow, among other things, diagnosis of cardiac conditions and selection of therapies treating the cardiac conditions. The cardiac rhythm management systems include systems having, for example, pacemakers, cardioverter/defibrillators, pacemaker/defibrillators, cardiac resynchronization therapy (CRT) devices, and cardiac remodeling control devices. However, it is to be understood that the present methods and apparatuses may be employed in other types of medical devices, including, but not being limited to, drug delivery systems and various types of cardiac monitoring devices.

**[0023]** More particularly, the cardiac rhythm management system discussed in this document generates and trends an S3 index indicative of S3 activity. The S3 index (or prevalence) is a ratio of the number of heart beats during which S3 are detected (“S3 beats”) to the number of all the heart beats. Because the S3 activity varies throughout the day, the S3 beats are counted for a plurality of measurement sessions distributed over a measurement period. The S3 index is then calculated for the measurement period and trended over multiple measurement periods. A trend of the S3 index provides for an indication of heart failure. For example, an increase in the trend of the S3 index may be indicative of abnormally restrictive filling and elevated filling pressures that lead to edema.

**[0024]** While this document particularly relates to S3, other heart sounds are also detected and/or analyzed for S3 detection and other purposes. Known and studied heart sounds include the “first heart sound” or S1, the “second heart sound” or S2, the “third heart sound” or S3, the “fourth heart sound” or S4, and their various sub-components. S1 is known to be indicative of, among other things, mitral valve closure, tricuspid valve closure, and aortic valve opening. S2 is known to be indicative of, among other things, aortic valve closure and pulmonary valve closure. S3 is known to be a ventricular diastolic filling sound often indicative of certain pathological conditions including heart failure. S4 is known to be a ventricular diastolic filling sound resulted from atrial contraction and is usually indicative of pathological conditions. The term “heart sound” hereinafter refers

to any heart sound (e.g., S1) and any components thereof (e.g., M1 component of S1, indicative of Mitral valve closure).

**[0025]** Throughout this document, “heart sound” includes audible and inaudible mechanical vibrations caused by cardiac activity that can be sensed with an accelerometer. Accordingly, when a mechanical sensor such as an accelerometer is used to sense the heart sounds, the scope of energy included in the sensed “acoustic signal” extends to energies associated with such mechanical vibrations. Unless noted otherwise, S1 refers to the first heart sound, S2 refers to the second heart sound, S3 refers to the third heart sound, and S4 refers to the fourth heart sounds, each as a heart sound type, or as one or more occurrences of the corresponding type heart sounds, depending on the context. A “heart beat” includes a cardiac cycle. An “S3 beat” includes a cardiac cycle during which S3 is detected. An “S3 index,” also referred to as an “S3 ratio,” includes a ratio of the number of the S3 beats to the number of the total heart hearts, both detected during the same time period.

**[0026]** Throughout this document, a “user” includes a physician or other caregiver who examines and/or treats a patient using one or more of the methods and apparatuses reported in the present document.

**[0027]** FIG. 1 is a block diagram illustrating an embodiment of a heart sound processing system 100 for trending the S3 index. Heart sound processing system 100 trends the S3 index by calculating an average ratio of the number of S3 beats to the total number of heart beats counted over predetermined measurement sessions. It includes a cardiac signal input 101, a beat counter 103, an acoustic signal input 104, a heart sound detector 105, a heart sound counter 106, an activity signal input 107, an activity detector 108, a measurement timer 109, a measurement delay timer 110, and a heart sound analyzer 112.

**[0028]** Cardiac signal input 101 receives cardiac signals indicative of cardiac events such as atrial and ventricular contractions. The cardiac signals include electrocardiographic (ECG) signals and/or event markers indicative of occurrences and timing of the cardiac events. In one embodiment, cardiac signal input 101 receives at least one ventricular electrogram (intracardiac ECG) acquired through at least one intracardiac electrode coupled to an implantable device. The ventricular electrogram is indicative of intrinsic ventricular events (sensed R-waves) and paced ventricular events (ventricular pacing pulses and/or paced R-waves). In another embodiment, cardiac signal input 101 receives at least one signal including event markers indicative of occurrences and timing of intrinsic and paced ventricular events. The intrinsic and paced ventricular events provide for heart beat detection and counting and serve as a timing reference for heart sound detections, as discussed below with reference to FIGS. 2 and 3.

**[0029]** Beat counter 103 counts the number of detected heart beats. In one embodiment, beat counter 103 counts one beat for each intrinsic or paced ventricular event.

**[0030]** Acoustic signal input 104 receives an acoustic signal indicative of one or more types of heart sounds including at least S3. In one embodiment, the acoustic signal is acquired by a microphone sensing acoustic energies generated by mechanical vibrations of the heart. In another embodiment, the acoustic signal is acquired by an accelerometer sensing energies associated with the mechanical vibrations of the heart, including both audible and inaudible

energies. In one further embodiment, the acoustic signal is a rectified and low-pass filtered signal, such as an acoustic signal 340 illustrated in FIG. 3.

**[0031]** Heart sound detector 105 detects at least S3 from the acoustic signal received by acoustic signal input 104. In one embodiment, heart sound detector also detects S1 and/or S2 during the process of detecting S3. Heart sound detector 105 is further discussed below with reference to FIG. 2.

**[0032]** Heart sound counter 106 counts the number of S3 beats. During each counted heart beat, if heart sound detector 105 detects an S3, heart sound counter 106 counts one S3 beat.

**[0033]** Activity signal input 107 detects a physical activity level of a person from whom the heart sounds are detected. When the acoustic signal is acquired by an accelerometer, physical activities may be sensed as a noise because the accelerometer senses both the heart’s vibrations and the person’s gross bodily movements. The physical activity level thus determines whether the heart sounds can be reliably detected, i.e., without detecting the person’s gross activities as heart sounds.

**[0034]** Activity detector 108 determines whether the physical activity level exceeds a threshold above which heart sound detection is considered unreliable. In one embodiment, activity detector 108 includes a comparator to compare the physical activity level to a predetermined threshold. Activity detector 108 generates a permission signal when the physical activity level is below the threshold. Measurement timer 109 starts and times measurement sessions during which the heart beats and the S3 beats are counted. In one embodiment, measurement timer 109 includes a measurement period timer and a measurement timer. Each measurement period includes a plurality of measurement sessions each start at prescheduled times. In one embodiment, adjacent measurement periods overlap. For example, measurement period M includes predetermined measurement sessions N, N+1, and N+2; measurement period M+1 includes predetermined measurement sessions N+1, N+2, and N+3; and so on. In another embodiment, measurement periods do not overlap. For example, measurement period M includes measurement sessions N, N+1, and N+2; measurement period M+1 includes measurement sessions N+3, N+4, and N+5; and so on. In one embodiment, a user determines and programs the timing of the measurement periods and the timing of the measurement sessions. In one specific embodiment, the user makes the determination based on the need and the conditions of a particular patient. In one embodiment, measurement timer 109 includes a measurement period clock to time a predetermined time interval as one measurement period. In another embodiment, measurement timer 109 includes a measurement period counter to count a predetermined number of measurement sessions as a measurement period. In one embodiment, measurement timer 109 includes a measurement session clock to time a predetermined time interval as one measurement session. In another embodiment, measurement timer 109 includes a measurement session counter to count a predetermined number of heart beats as one measurement session. Measurement timer 109 starts a measurement session only when the output of activity detector 108 represents a permission signal. In one specific embodiment, the measurement period is one day and includes about 4 to 48 measurement sessions, depending on the patient’s circumstances, and each measurement session lasts for about

10 to 30 beats. Measurement delay timer 110 delays the start of a measurement session when a scheduled measurement session is prevented from starting by an absence of the permission signal. In one embodiment, measurement delay timer 110 delays the start of a measurement session until the permission signal is given by activity detector 108. In another embodiment, measurement delay timer 110 checks the presence of the permission signal periodically with a predetermined delay period, and allows the start of a measurement session when the permission signal is present at the end of one of the predetermined delay periods.

[0035] Heart sound analyzer 112 generates a trend of S3 index based on a ratio of the number of S3 beats to the number of total heart beats counted during a predetermined time period (the S3 index or S3 ratio). In one embodiment, the ratio is expressed as a percentage (the S3 percentage). Heart sound analyzer 112 includes a ratio calculator 113, an averaging module 114, and a trend generator 115. In one embodiment, ratio calculator 113 receives the number of the S3 beats and the number of the heart beats counted during each measurement session and calculate the S3 ratio for each measurement session, resulting in an S3 session ratios (i.e., S3 indexes for the measurement sessions). In one specific embodiment, ratio calculator 113 includes a percentage calculator to calculate the S3 percentage for the measurement session, resulting in S3 session percentages. In another embodiment, ratio calculator 113 estimates the S3 ratio for each measurement session based on some but not all the beats (such as every other beat), for example, when detecting and/or counting each and every beat and/or S3 beat is impractical. Averaging module 114 calculates an average of the S3 session ratios over each measurement period to result in S3 periodic ratios (i.e., S3 indexes for the measurement periods). Trend generator 115 generates the trend of S3 index as a moving S3 periodic ratio over a plurality of the measurement periods, where each S3 periodic ratio is an average of the S3 session ratios for one of the measurement periods. In an alternative embodiment, ratio calculator 113 receives the number of the S3 beats and the number of the heart beats counted during each measurement period and calculate the S3 ratio for that measurement period, directly resulting in S3 periodic ratios. Trend generator 115 generates the trend of S3 index as a moving S3 periodic ratio over a plurality of the measurement periods. In one embodiment, trend generator 115 generates the trend of S3 index as a plot of daily S3 ratios over multiple days.

[0036] FIG. 2 is a block diagram illustrating an embodiment of heart sound detector 105. Heart sound detector 105 detects S3 by using the method illustrated in FIG. 3. FIG. 3 shows an acoustic signal 340 indicative of an S1 occurrence 341, an S2 occurrence 342, and an S3 occurrence 343 during one cardiac cycle. In one embodiment, acoustic signal 340 represents an output signal of an envelope detector that rectifies and low-pass filters a sensor signal indicative of heart sounds. Acoustic input 104 receives acoustic signal 340. In one embodiment, the S3 detection method employed by heart sound detector 105 provides for detection of at least S2 and S3. Detection of S1 is required for the detection of S3 when the amplitude and/or energy of S1 are needed to adjust one or more detection thresholds including an S2 threshold 346 and an S3 threshold 347.

[0037] S2 and S3 detections are repeated for each cardiac cycle when the heart sounds are being detected. S2 detection includes comparing the amplitude of acoustic signal 340 to

S2 threshold 346 during an S2 window 354. S2 window has a predetermined temporal relationship with a ventricular (V) event detection 349, such as an R-wave or a delivery of a ventricular pacing pulse. As illustrated in FIG. 3, V event detection 349 starts a predetermined S2 window delay 355. S2 window 354 starts when S2 window delay 355 expires. S2 detection occurs when the amplitude of acoustic signal 340 exceeds S2 threshold 346 during S2 window 354. S2 window delay 355 and the duration of S2 window 354 are programmed on a patient-by-patient basis. In one embodiment, the timing of S2 detection 350 is empirically estimated for each individual patient and dynamically adjusted based on the patient's heart rate. In one specific example, the time interval between V event detection 349 and S2 detection 350,  $T_{V-S2}$ , is estimated by:  $T_{V-S2} = 0.500 - 0.002 \text{ HR seconds}$ , where HR is heart rate in beats per minute, and 0.500 seconds is empirically derived for the individual patient. Then, the duration of S2 window 354 is empirically derived for that patient, and S2 window 354 is centered at the estimated time for S2 detection 350, i.e., end of  $T_{V-S2}$ . S2 window delay is, therefore,  $T_{V-S2}$  minus a half of the duration of S2 window 354. S3 detection includes comparing the amplitude of acoustic signal 340 to S3 threshold 347 during an S3 window 356. S3 window has a predetermined temporal relationship with S2 detection 350. An S3 window delay 357 starts with S2 detection 350. S3 window 356 starts when S3 window delay 357 expires. S3 detection occurs when the amplitude of acoustic signal 340 exceeds S3 threshold 347 during S3 window 356. S3 window delay 357 and the duration of S3 window 356 are programmed on a patient-by-patient basis. In one embodiment, S3 window delay 357 is programmable between 100 and 200 milliseconds. The duration of S3 window 356 is programmable to about 150 ms but is terminated by V event 349 of the next cardiac cycle it occurs before the end of the programmed duration.

[0038] As illustrated in FIG. 2, heart sound detector 105 includes a heart rate detector 220, an S1 detector 222, an S2 detection module (including an S2 detection preparation module, an S2 window generator 225, an S2 threshold generator 226, and an S2 detector 227), an S3 detection module (including an S3 detection preparation module, an S3 window generator 230, an S3 threshold generator 231, and an S3 detector 232), and a measurement module 234. Heart rate detector 220 detects a heart rate from the cardiac signal such as the signal received by cardiac signal input 101.

[0039] S1 detector is required when S3 threshold 347 depends at least partially on the S1 amplitude or energy. It is also required when, as part of an overall signal processing and analysis scheme, measurement related to S1 are taken.

[0040] S2 detection preparation module 224, S2 window generator 225, S2 threshold generator 226, and S2 detector 227 perform S2 detection. S2 detection preparation module 224 is needed when acoustic signal 340 needs to be further processed to facilitate an accurate S2 detection. In one embodiment, S2 detection preparation module 224 includes an averaging circuit that improves the signal-to-noise ratio of acoustic signal 340 by ensemble averaging. In one specific embodiment, the averaging circuit aligns multiple segments of acoustic signal 340 by V event markers representing V event detection 349 on each segment. The segments of acoustic signal 340 to be included for the ensemble averaging are selected from segments of acoustic signal 340

associated with consecutive cardiac cycles with a relatively constant heart rate (e.g., within about 10 to 20 beats per minute variation). S2 window generator 225 includes an S2 window delay timer to time S2 window delay 355 and an S2 window timer to time S2 window 354. V event detection 349 (represented by such as an event marker include in the cardiac signal) triggers the S2 window delay timer to start timing S2 window delay 355. The expiration of S2 window delay 355 triggers the S2 window timer to time S2 window 354, during which S2 is being detected. S2 threshold generator 226 generates S2 threshold 346 based on the amplitude of S1 and/or the amplitude of S2. In one embodiment, S2 threshold generator 226 dynamically adjusts S2 threshold 346 based on the amplitude of S1 and/or the amplitude of S2 averaged over a moving window including a plurality of heart beats. S2 detector 227 includes a comparator to compare acoustic signal 340 to S2 threshold 346, and detects an occurrence of S2 when the amplitude of acoustic signal 340 exceeds S2 threshold 346 during S2 window 354.

[0041] S3 detection preparation module 229, S3 window generator 230, S3 threshold generator 231, and S3 detector 232 perform the S3 detection. S3 detection preparation module 229 is needed when acoustic signal 340 needs to be further processed to facilitate an accurate S3 detection. In one embodiment, S3 detection preparation module 229 includes the averaging circuit of S2 detection preparation module 224, and the averaged acoustic signal is used for both S2 and S3 detection. In one specific embodiment, S3 detection preparation module 229 and S2 detection preparation module 224 includes a single averaging circuit—the same averaging circuit that performs the ensemble averaging discussed above. In another embodiment, S3 detection preparation module 229 includes an averaging circuit for the purpose of S3 detection only. This averaging circuit improves the signal-to-noise ratio of acoustic signal 340 for the S3 detection by an ensemble averaging process. The averaging circuit aligns multiple segments of acoustic signal 340 by S2 markers representing S2 detection 350 on each segment, where the S2 detection 350 is resulted from S2 detection performed on acoustic signal 340 before the ensemble averaging. The segments of acoustic signal 340 to be included for the ensemble averaging are selected from segments of acoustic signal 340 associated with consecutive cardiac cycles with a relatively constant heart rate (e.g., within about 10 to 20 beats per minute variation). S3 window generator 230 includes an S3 window delay timer to time S3 window delay 357 and an S2 window timer to time S3 window 356. S3 detection 350 triggers the S3 window delay timer to start timing S3 window delay 357. The expiration of S3 window delay 357 triggers the S3 window timer to time S3 window 356, during which S3 is being detected. S3 threshold generator 231 generates S3 threshold 347. In one embodiment, S3 threshold generator 231 determines S3 threshold 347 based on one or more of an S1 amplitude and an S2 amplitude. In one specific embodiment, S3 threshold generator 231 determines S3 threshold 347 as a percentage of the S2 amplitude. In another embodiment, S3 threshold generator 231 determines S3 threshold 347 based on a total acoustic energy in one cardiac cycle. The purpose is to normalize S3 threshold 347 by the total acoustic energy, such that the S3 detection remains accurate when external variables causes the amplitude of acoustic signal 340 to shift. The total acoustic energy is calculated by integrating acoustic signal 340 over one cardiac cycle or

adding the estimated energies of S1, S2, and S3 (if present). In one specific example, S3 threshold generator 231 determines S3 threshold 347 based on at least a mean and a standard deviation of the total acoustic energy in the cardiac cycle. In another embodiment, S3 threshold generator 231 determines S3 threshold 347 based on a total acoustic energy during systole of one cardiac cycle. The total acoustic energy is calculated by integrating acoustic signal 340 over the time interval between V event detection 349 and the beginning of S3 window 356 or adding the estimated energies of S1 and S2. In one specific embodiment, S3 threshold generator 231 determines S3 threshold 347 based on at least a mean and a standard deviation of the total acoustic energy during systole of the cardiac cycle. In another embodiment, S3 threshold generator 231 determines S3 threshold 347 based on a temporal average of one or more of the S1 amplitude, the S2 amplitude, and the total acoustic energy in one cardiac cycle. In another embodiment, S3 threshold generator 231 determines S3 threshold 347 based on an estimated background sound level 345 ( $\mu_B$ ) measured during a background estimate period 353, which is a predetermined period between S1 and S2, as illustrated in FIG. 3. Background estimate period 353 is centered between  $T_{S1max}$  and  $T_{S2min}$ , where  $T_{S1max}$  is the latest point in time where S1 energy is expected, and is  $T_{S2min}$  is the point in time where S2 window 354 begins. In one embodiment,  $T_{S1max}$  is empirically estimated based on a patient population. In one embodiment,  $T_{S1max}$  is in a range of about 100 to 200 millisecond after V event detection 349. In one embodiment, the duration of background estimate period 353 substantially equals to the time interval between  $T_{S1max}$  and  $T_{S2min}$ . In another embodiment, the duration of background estimate period 353 is shorter than the time interval between  $T_{S1max}$  and  $T_{S2min}$ . In another embodiment, the duration of background estimate period 353 is set to be equal to the time interval between  $T_{S1max}$  and  $T_{S2min}$  but subjected to a maximum duration and a minimum duration. The duration of background estimate period 353 is set to the maximum duration if the time interval between  $T_{S1max}$  and  $T_{S2min}$  is longer than the maximum duration and to the minimum duration if the time interval between  $T_{S1max}$  and  $T_{S2min}$  is shorter than the minimum duration. In one embodiment, S3 threshold generator 231 scales background estimate period 353 for the detected heart rate. S3 threshold 347 is a function of pm In one specific embodiment, S3 threshold generator 231 sets and dynamically adjusts S3 threshold 347 to  $\mu_B * K$ , where K is a programmable constant. In one embodiment, K is a constant determined, and can be later adjusted, by a user. In one embodiment, K is a constant false alarm rate (CFAR) as known in the art of signal processing. S3 detector 232 includes a comparator to compare acoustic signal 340 to S3 threshold 347, and detects an occurrence of S3 when the amplitude of acoustic signal 340 exceeds S3 threshold 347 during S3 window 356. Measurement module 234 measures parameters from detected S1, S2 and/or S3.

[0042] In one embodiment, the measured parameters are used to set and adjust S2 threshold 346 and/or S3 threshold 347. In another embodiment, the measured parameters are used for various cardiac functional analysis based on or related to heart sounds. In one embodiment, measurement module 234 includes an amplitude detector to detect amplitudes of S1, S2, and/or S3. In one further embodiment, measurement module 234 includes an energy detector to detect energies associated with S1, S2, and/or S3. Examples

of other parameters measured by measurement module 234 include, but are not limited to, duration of any type heart sound, fundamental and/or harmonic frequencies of any heart sound, time interval between any two heart sounds, and time interval between an intrinsic or paced cardiac event detected from the electrogram and a heart sound detected from the acoustic signal.

[0043] FIG. 4 is a flow chart illustrating an embodiment of a method for trending the S3 index. In one embodiment, the method is performed using heart sound processing system 100. The method includes acquiring cardiac and acoustic signals at 400, timing S3 index trending at 420, and trending the S3 index at 440.

[0044] Cardiac and acoustic signals required for trending the S3 index are sensed and preprocessed at 400. At 402, an acoustic signal is sensed. In one embodiment, this includes sensing an audio signal generated from a heart using a microphone placed in or near the heart. In another embodiment, this includes sensing a mechanical vibration of the heart using an accelerometer placed in or near the heart. The acoustic signal is preprocessed at 404. In one embodiment, this includes performing envelope detection, i.e., rectifying and low-pass filtering the sensed acoustic signal. One example of a resultant preprocessed acoustic signal is illustrated as acoustic signal 340 in FIG. 3. At 406, at least one electrogram is sensed. In one embodiment, this includes sensing a ventricular electrogram with at least one electrode placed a ventricular chamber of the heart to sense ventricular events. A cardiac signal is produced at 408. In one embodiment, this includes detecting cardiac events indicated in the sensed electrogram and producing event markers each indicative of an occurrence of the detected cardiac events, including its type and timing. In one specific example, the cardiac signal includes ventricular event markers representing sensed ventricular contractions and/or deliveries of ventricular pacing pulses.

[0045] The heart sound analysis producing the trend of the S3 index is a periodic process timed at 420. The timing includes timing measurement periods each including a plurality of measurement sessions. In one embodiment, the measurement period is a predetermined time period defined as a number of hours, days, weeks, etc. Each measurement period includes a plurality of prescheduled measurement sessions. In one embodiment, a physical activity level is detected at 422. The physical activity level indicates a person's gross bodily movements that may interfere with the sensing of the acoustic signal. A permission signal is issued at 424 to allow the start of a measurement session if the physical activity level is below a threshold level indicating that the person is resting. If the permission signal is present when a measurement session is scheduled to begin, a measurement session is timed at 426. In one embodiment, the measurement session is timed as a predetermined period of time. In another embodiment, the measurement session is timed by counting a predetermined number of heart beats. If the permission signal is absent when a measurement session is scheduled to begin, the measurement session is postponed for a predetermined period of time or until the physical activity level falls below the threshold level. In one embodiment, timing S3 index trending at 420 also includes timing the acquisition of the cardiac and acoustic signals.

[0046] A trend of the S3 index is produced at 440. The cardiac signal produced at 408 and the acoustic signal preprocessed at 404 are received at 442. Heart beats are

counted at 444 for each measurement session or period, based on one type of cardiac events included in the cardiac signal. In one embodiment, one heart beat is counted for each ventricular event. Occurrences of S3 are detected at 446. The S3 beats are counted at 448 for each measurement session or period. The S3 index is calculated at 450, as the ratio of the number of S3 beats to the number of total heart beats counted during the measurement session or period. In one embodiment, the ratio is expressed as a percentage. The trend of the S3 index is produced at 452. In one embodiment, the trend of the S3 index is a moving S3 index calculated for the measurement periods. In another embodiment, the trend of the S3 index is a moving average of the S3 index calculated for the measurement sessions over the measurement periods. In one embodiment, trend of the S3 index is presented as a plot of S3 indices over a measured period or another predetermined period. In one specific embodiment, trend of the S3 index is presented as a plot of daily S3 indices.

[0047] FIG. 5 is a flow chart illustrating an embodiment of a method for detecting S3. In one embodiment, the method is performed using heart sound detector 105. The method includes acquiring cardiac and acoustic signals at 500, detecting heart sounds at 520, and measuring parameters related to the detected heart sounds at 550.

[0048] Cardiac and acoustic signals are sensed and preprocessed at 500. At 502, an acoustic signal is sensed. In one embodiment, this includes sensing an audio signal generated from a heart using a microphone placed in or near the heart. In another embodiment, this includes sensing a mechanical vibration of the heart using an accelerometer placed in or near the heart. The acoustic signal is envelope-detected, i.e., rectified and low-pass filtered, at 504. One example of the envelope-detected acoustic signal is illustrated as acoustic signal 340 in FIG. 3. At 506, a ventricular electrogram is sensed. A cardiac signal is produced at 508. This includes detecting ventricular events, including sensed ventricular contractions and/or deliveries of ventricular pacing pulses, and generating ventricular event markers representing the detected ventricular events. In one embodiment, when the S3 index trending method (illustrated in FIG. 4) employs the S3 detection method (illustrated in FIG. 5), step 400 and step 500 include substantially the same steps.

[0049] Heart sounds including S1, S2, and/or S3 are detected at 520. The cardiac signal and the acoustic signal are received at 522. S1 is detected at 524. In one embodiment, detecting S1 includes comparing the amplitude of the preprocessed acoustic signal to an S1 threshold. An S2 window is generated at 526. An S2 threshold is determined at 528. S2 is detected at 530. In one embodiment, steps 526, 528, and 530 are performed using the method discussed above with reference to FIG. 3. An S3 window is generated at 532. An S3 threshold is determined at 534. S3 is detected at 536. In one embodiment, steps 532, 534, and 536 are performed using the method discussed above with reference to FIG. 3.

[0050] Parameters are measured from the detected heart sounds at 550. In one embodiment, the parameters are used to determine the S1 threshold, the S2 threshold, and/or the S3 threshold. Amplitudes of S1, S2, and/or S3 are measured at 552. In one embodiment, each amplitude is measured as an average of amplitudes of one type heart sound measured over a plurality of heart beats. Energies associated with S1, S2, and/or S3 are measured at 554. In one embodiment, each

energy is measured as an average of energies associated with one type heart sound measured over a plurality of heart beats. A total acoustic energy during a cardiac cycle is measured (and/or calculated) at **556**. In one embodiment, the total acoustic energy during the cardiac cycle is measured as an average over a plurality of cardiac cycles (heart beats). A total acoustic energy during systole is measured (and/or calculated) at **558**. In one embodiment, the total acoustic energy during systole is measured as an average over a plurality of heart beats.

**[0051]** In one embodiment, one or more parameters measured at **550** are used for analyzing cardiac conditions. One example of such parameter measurement and use is discussed in U.S. patent application Ser. No. 10/334,694, entitled "METHOD AND APPARATUS FOR MONITORING OF DIASTOLIC HEMODYNAMICS," filed Dec. 30, 2002, now issued as U.S. Pat. No. 7,972,275, assigned to Cardiac Pacemakers, Inc., the specification of which is incorporated herein by reference in its entirety.

**[0052]** FIGS. 4 and 5 are for illustrative purposes and do not necessarily reflect the exact temporal order by which the steps are performed in practice. The actual order or sequence by which the steps are performed depends on logic and design considerations.

**[0053]** FIG. 6 is an illustration of an embodiment of portions of a cardiac rhythm management system **699** incorporating heart sound processing system **100**, and portions of an environment in which it is used. In one embodiment, cardiac rhythm management system **699** includes an implantable system **665**, an external system **670**, and a telemetry link **669** providing for communication between implantable system **665** and external system **670**.

**[0054]** Implantable system **665** includes an implantable device **667** and a lead system **668**. Implantable device **667** is implanted within a patient's body **662** and electrically connected to the patient's heart **661** via lead system **668**. Examples of implantable device **667** include pacemakers, cardioverter/defibrillators, pacemaker/defibrillators, cardiac resynchronization devices, cardiac remodeling control devices, and drug delivery devices.

**[0055]** In one embodiment, external system **670** includes an external device **671** in proximity of implantable device **667**, a remote device **673** in a relatively distant location, and a telecommunication system **672** linking external device **671** and remote device **673**. An example of such an external system includes an advanced patient management system discussed in U.S. patent application Ser. No. 10/323,604, entitled "ADVANCED PATIENT MANAGEMENT FOR DEFINING, IDENTIFYING AND USING PREDETERMINED HEALTH-RELATED EVENTS," filed on Dec. 18, 2002, assigned to Cardiac Pacemakers, Inc., the specification of which is incorporated herein by reference in its entirety. In another embodiment, external system **670** includes an implantable medical device programmer.

**[0056]** In one embodiment, telemetry link **669** is an inductive telemetry link. In an alternative embodiment, telemetry link **669** is a far-field radio-frequency telemetry link. In one embodiment, telemetry link **669** provides for data transmission from implantable device **667** to external device **671**. This may include, for example, transmitting real-time physiological data acquired by implantable device **667**, extracting physiological data acquired by and stored in implantable

device **667**, extracting therapy history data stored in implantable device **667**, and extracting data indicating an operational status of implantable device **667** (e.g., battery status and lead impedance). In a further embodiment, telemetry link **669** provides for data transmission from external device **671** to implantable device **667**. This may include, for example, programming implantable device **667** to acquire physiological data, programming implantable device **667** to perform at least one self-diagnostic test (such as for a device operational status), and programming implantable device **667** to deliver at least one therapy.

**[0057]** In one embodiment, programming implantable device **667** includes sending therapy parameters to implantable device **667**. The therapy parameters provide an improved hemodynamic performance for a patient by delivering cardiac pacing pulses to the patient's heart. In one embodiment, the therapy parameters providing for the improved hemodynamic performance are determined by monitoring one or more ventricular diastolic hemodynamics as indicated by parameters related to heart sounds. Such parameters indicate the heart's mechanical activities and electromechanical association. In one specific embodiment, the parameters related to heart sounds are measured by heart sound processing system **100**, as discussed above with reference to FIGS. 1-3.

**[0058]** FIG. 7 is a block diagram illustrating a specific embodiment of portions of cardiac rhythm management system **699**. Cardiac rhythm management system **699** includes implantable system **665**, external system **670**, and a telemetry link **669** wirelessly coupling these two systems. Heart sound processing system **100** is included in implantable system **665** and/or external system **670**. The actual distribution of heart sound processing system **100** in implantable system **665** and/or external system **670** depends on practical considerations such as power and size constraints of an implantable device, telemetry capability, and systemic factors such as efficiency of operation and convenience of use of cardiac rhythm management system **699**. In one embodiment, implantable system **665** includes the entire heart sound processing system **100**. In another embodiment, external system **670** includes the entire heart sound processing system **100**. In another embodiment, implantable system **665** includes portions of heart sound processing system **100** and external system **670** includes the remaining portions of heart sound processing system **100**.

**[0059]** Implantable system **665** includes implantable device **667** and lead system **668**. Lead system **668** electrically connects implantable device **667** to heart **661**. In one embodiment, implantable device **667** includes a hermetically sealed can to house an implantable acoustic sensor **780**, a sensor processing circuit **781**, a cardiac sensing circuit **784**, a cardiac event detector **785**, an implant controller **782**, an implant heart sound processor **786**, and an implant telemetry module **775**. In another embodiment, implantable acoustic sensor **780** is incorporated into a lead of lead system **668**. Implantable acoustic sensor **780** senses the acoustic signal indicative of the heart's mechanical vibrations, i.e., heart sounds, of heart **661**. In one embodiment, implantable acoustic sensor **780** includes an accelerometer. In another embodiment, implantable acoustic sensor **780** includes a microphone. Sensor processing circuit **781** preconditions the sensed acoustic signal for further processing by heart sound

processing system **100**. In one embodiment, the acoustic signal is envelope detected. Sensor processing circuit **781** includes a rectifier and a low-pass filter to perform the envelope detection. Cardiac sensing circuit **784** includes sense amplifiers and filters to sense one or more electrograms. In one embodiment, cardiac sensing circuit **784** senses at least a ventricular electrogram indicative of ventricular events including intrinsic ventricular contractions and ventricular pacing pulse deliveries. Cardiac event detector **785** detects predetermined types of cardiac events. In one embodiment, cardiac event detector **785** detects the ventricular events including the intrinsic ventricular contractions and the ventricular pacing pulse deliveries. In one embodiment, cardiac event detector **785** generates event markers to represent the detected events. The event markers each indicate an occurrence, a timing of the occurrence, and a type of the detected event represented. Implant controller **782** controls the overall operation of implantable system **665**. In one embodiment, implant heart sound processor **786** includes at least a portion of heart sound processing system **100**. In one specific embodiment, implant heart sound processor **786** includes substantially the entire heart sound processing system **100**. Implant telemetry module **775** is the portion of the circuit supporting telemetry link **669** that resides in implantable system **665**.

[0060] External system **670** includes an external telemetry module **776** and an external heart sound module **778**. External telemetry module **776** is the portion of the circuit supporting telemetry link **669** that resides in external system **670**. External heart sound module **778** includes an external heart sound processor **790**. In one embodiment, external heart sound processor **790** includes at least a portion of heart sound processing system **100**. In one specific embodiment, external heart sound processor **790** includes substantially the entire heart sound processing system **100**. In one embodiment, external heart sound processor **790** is substantially included in external device **671** of external system **670**. In another embodiment, external heart sound processor **790** is substantially included in remote device **673** of external system **670**. In another embodiment, external heart sound processor **790** is distributed in both external device **671** and remote device **673**.

[0061] In one embodiment, in addition to the functions of external heart sound processor **790**, external heart sound module **778** analyzes parameters derived from detected cardiac events and heart sounds. Examples of such analyses are discussed in U.S. patent application Ser. No. 10/307,896, "PHONOCARDIOGRAPHIC IMAGE-BASED ATRIO-VENTRICULAR DELAY OPTIMIZATION," filed Dec. 12, 2002, now issued as U.S. Pat. No. 7,123,962, and U.S. patent application Ser. No. 10/334,694, entitled "METHOD AND APPARATUS FOR MONITORING OF DIASTOLIC HEMODYNAMICS," filed December 30, 2002, now issued as U.S. Pat. No. 7,972,275, both assigned to Cardiac Pacing, Inc., the specifications of which are incorporated herein by reference in their entirety.

[0062] It is to be understood that the above detailed description is intended to be illustrative, and not restrictive. For example, heart sound processing system **100** may be incorporated into any implanted or external medical device providing for ECG and heart sound monitoring. Other embodiments will be apparent to those of skill in the art upon reading and understanding the above description. The scope of the invention should, therefore, be determined with

reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

1. (canceled)
2. A medical system, comprising:
  - a heart sound detector configured to:
    - determine a second heart sound (S2) timing estimate using a received heart sound signal and heart rate information;
    - determine a third heart sound (S3) window with respect to the determined S2 timing estimate; and
    - measure an S3 amplitude using at least a portion of the heart sound signal within the determined S3 window; and
  - a heart failure detector configured to detect a condition indicative of worsening heart failure (WHF) using the measured S3 amplitude.
3. The system of claim 2, wherein the S3 amplitude includes signal energy of at least the portion of the heart sound signal within the determined S3 window.
4. The system of claim 2, wherein the S3 window begins at a first delay with respect to the determined S2 timing estimate, wherein the first delay is programmable between 100 and 200 milliseconds.
5. The system of claim 2, wherein the heart sound detector, to detect the S2 timing estimate, is configured to:
  - determine a S2 window from the heart sound signal, the S2 window starting at a second delay with respect to a ventricular event, the second delay dynamically adjusted according to the heart rate information; and
  - determine the S2 timing estimate corresponding to a timing when the heart sound signal exceeds a S2 threshold during the determined S2 window.
6. The system of claim 2, wherein the second delay is linearly related to a heart rate.
7. The system of claim 2, further comprising a therapy control circuit configured to deliver a heart failure therapy based on the detected condition indicative of WHF.
8. The system of claim 2, wherein the heart failure detector is configured to:
  - generate an S3 index trend using measurements of S3 amplitude within a specified time period; and
  - detect the condition indicative of WHF using the S3 index trend.
9. The system of claim 8, wherein the S3 index trend includes a plurality of S3 indices indicative of prevalence of S3 activity, the S3 indices each generated using measurements of S3 amplitude within a respective measurement period that includes a plurality of heart beats.
10. The system of claim 9, wherein the S3 indices each includes a ratio of (1) a count of S3 amplitude measurements, within the respective measurement period, that exceeds an S3 amplitude threshold to (2) a count of the plurality of heart beats within the respective measurement period.
11. The system of claim 10, wherein the S3 amplitude threshold is determined based on signal energy of at least a portion of the heart sound signal within a cardiac cycle.
12. The system of claim 11, wherein the S3 amplitude threshold is determined based on signal energy of the heart sound signal during systole of the cardiac cycle.
13. The system of claim 2, comprising an accelerometer configured for sensing the heart sound signal including a cardiac vibration signal.

**14.** The system of claim **2**, comprising a microphone configured for sensing the heart sound signal including a cardiac audio signal.

**15.** A method for operating a medical system, the method comprising:

determining, via a heart sound detector, a second heart sound (S2) timing estimate using a received heart sound signal and heart rate information;

determining, via the heart sound detector, a third heart sound (S3) window with respect to the determined S2 timing estimate;

measuring, via the heart sound detector, an S3 amplitude using at least a portion of the received heart sound signal within the determined S3 window; and

detecting, via a heart failure detector, a condition indicative of worsening heart failure (WHF) using the measured S3 amplitude.

**16.** The method of claim **15**, further comprising:

generating an S3 index using measurements of S3 amplitude over a specified measurement period that includes a plurality of heart beats, the S3 index indicative of prevalence of S3 activity; and

generating an S3 index trend over a plurality of the specified measurement periods, the S3 index trend including a plurality of S3 indices;

wherein the detecting the condition indicative of worsening heart failure (WHF) is at least based on the generated S3 index trend.

**17.** The method of claim **15**, wherein the S3 amplitude includes signal energy of at least the portion of the heart sound signal within the determined S3 window.

**18.** The method of claim **15**, wherein the S3 window begins at a first delay with respect to the determined S2 timing estimate, and

wherein the determining the S2 timing estimate includes:

determining an S2 window from the heart sound signal, the S2 window starting at a second delay with respect to a ventricular event, the second delay dynamically adjusted according to the heart rate information; and

determining the S2 timing estimate corresponding to a timing when the heart sound signal exceeds a S2 threshold during the determined S2 window.

**19.** The method of claim **16**, wherein the generating an S3 index includes producing a ratio of (1) a count of S3 amplitude measurements, within the specified measurement period, that exceeds an S3 amplitude threshold to (2) a count of the plurality of heart beats within the specified measurement period.

**20.** The method of claim **19**, further comprising determining the S3 amplitude threshold based on signal energy of at least a portion of the heart sound signal within a cardiac cycle.

**21.** The method of claim **16**, further comprising delivering a heart failure therapy based on the detected condition indicative of WHF.

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