(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 June 2006 (29.06.2006)

PCT

(10) International Publication Number
WO 2006/069033 A1

(51) International Patent Classification:
A61N 1/37 (2006.01)

(21) International Application Number:
PCT/US2005/046055

(22) International Filing Date:
20 December 2005 (20.12.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/637,620 20 December 2004 (20.12.2004) US

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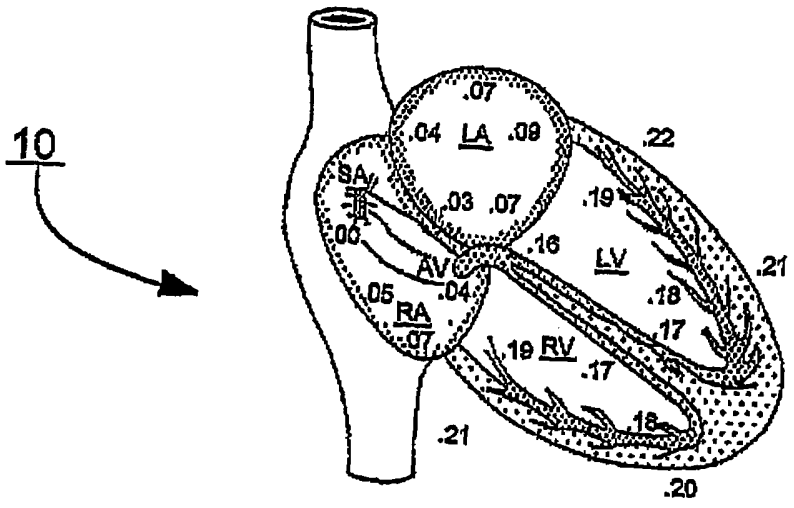
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title:** AUTOMATIC LV / RV CAPTURE VERIFICATION AND DIAGNOSTICS



(57) **Abstract:** The present invention provides a technique for verifying pacing capture of a ventricular chamber, particularly to ensure desired delivery of a ventricular pacing regime (e.g., cardiac resynchronization therapy or "CRT"). The invention also provides for ventricular capture management by delivering a single ventricular pacing stimulus and checking inter-ventricular conduction during a temporal window to determine if the ventricular pacing stimulus captured the chamber. If a loss-of-capture (LOC) signal results from the capture management testing, then the characteristics of the applied pacing pulses are modified and the conduction test repeated. In the event that the LOC signal persists, a pacing mode-switch to an atrial-based pacing therapy and/or non-bi-ventricular pacing regimen can be implemented.

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AUTOMATIC LV / RV CAPTURE VERIFICATION AND DIAGNOSTICS

FIELD OF THE INVENTION

The invention pertains to cardiac pacing systems and relates to apparatus and methods for automatically verifying pacing capture of a ventricular chamber. In particular, the invention relates to verification of pacing capture for both ventricular chambers during a cardiac resynchronization therapy (CRT) delivery, such as a bi-ventricular pacing therapy or uni-directional fusion-type CRT delivery.

BACKGROUND OF THE INVENTION

Cardiac resynchronization cardiac pacing devices operate by either delivering pacing stimulus to both ventricles or to one ventricle with the desired result of a more or less simultaneous mechanical contraction and ejection of blood from the ventricles. However, due to a number of factors for a variety of patients such cardiac pacing systems may not always effectively delivery CRT. For example, varying capture thresholds, pacing lead and/or electrode migration or dislodgement, time required for appropriate signal processing, confounding conduction delays or conduction blockages, diverse electrode placement locations, and the like.

In either form of CRT delivery, whether fusion-based or the more traditional bi-ventricular stimulation, confirming that pacing stimulus captures each paced ventricle is a very important clinical issue so that the desired benefits of the CRT are in fact delivered to a patient.

Assuming that the reader is familiar with bi-ventricular pacing, the following should provide additional insight into the importance of capture detection in a fusion-based bi-ventricular pacing engine. One premise underlying fusion-based pacing is the notion that a fusion-based evoked left ventricular (LV) depolarization enhances stroke volume in hearts where the right ventricle (RV) depolarizes first. This is commonly due to intact atrio-ventricular (AV) conduction to the RV of a preceding intrinsic or evoked atrial depolarization wave front, and wherein the AV conducted depolarization of the LV is unduly delayed. The fusion depolarization of the LV is attained by timing the delivery of the LV pace (LVp) pulse to follow the intrinsic depolarization of the RV but to precede the

intrinsic depolarization of the LV. Specifically, an RV pace (RVp) pulse is not delivered due to the inhibition of the RVp event upon the sensing of RV depolarization (RVs), allowing natural propagation of the wave front and depolarization of the intraventricular septum, while an LVp pulse is delivered in fusion with the RV depolarization (the LVp can also be delivered before the RVs, typically based on recent conduction timing). For supporting mode switches to alternate pacing modalities, fusion-based CRT delivery engines typically include at least one electrode in each ventricle which allows such engines to be used in conjunction with the present invention, as will be apparent upon review of the following written description and drawings of the invention.

Left ventricular capture in particular is a clinical issue with present-generation (and foreseeable) CRT systems, due to acknowledged difficulty of maintaining stable lead situation in the cardiac venous anatomy. Since CRT delivery becomes ineffective (possibly even deleterious) if LV capture is lost, diagnosis of dislodgment and maintenance of capture are high priorities.

Cardiac Resynchronization Therapy (CRT) devices have been shown to improve quality of life (QOL), exercise capacity and New York Heart Association (NYHA) heart failure class. The NYHA rating varies from Class I to Class IV, as follows: Class I: patients with no limitation of activities; they suffer no symptoms from ordinary activities. Class II: patients with slight, mild limitation of activity; they are comfortable with rest or with mild exertion. Class III: patients with marked limitation of activity; they are comfortable only at rest. Class IV: patients who should be at complete rest, confined to bed or chair; any physical activity brings on discomfort and symptoms occur at rest.

Currently approved CRT devices incorporate bi-ventricular pacing technology with simultaneous or sequential pacing in the right ventricle (RV) and the left ventricle (LV). Since the devices are implanted for the essentially only to provide continuous bi-ventricular pacing therapy, it is imperative that the each pacing pulse stimulus delivered to the two LV and RV provide an evoked response (i.e., each stimulus delivered to a ventricle "captures" the ventricle). Thus, if electrodes disposed in electrical communication with a ventricle rapidly sense depolarization wavefronts a control sequence for the pacing engine will inhibit ventricular pacing. For example, such a situation occurs during rapidly conducted atrial fibrillation (AF). When bi-ventricular pacing is inhibited the patient's symptoms of heart failure return, and can sometimes even worsen as compared to their

pre-implant status. Similarly, if one of the pacing sites loses capture (e.g., the LV) the subsequent RV-only pacing will prevent the patient from receiving the intended benefit of CRT delivery. To that end the inventors have addressed a need in the art regarding capture verification in heart failure devices, such as bi-ventricular CRT devices that indicates when capture is occurring in both the LV and the RV.

Presently, the only somewhat similar diagnostic available in CRT devices is percent-ventricular pacing (%Vpacing), which indicates the percentage of time bi-ventricular pacing therapy is being delivered; however, a limitation of the %Vpacing metric is that bi-ventricular pacing may be "occurring" close to 100% of the time but the LV chamber may not be captured at all. Currently, cardiac device specialists assess LV capture acutely during office visits by looking at the morphology of an electrogram (EGM) or by temporarily setting pacing to RV-only and LV-only pacing. Current state of the art pacemakers (e.g., the Kappa® brand family of pacemakers provided by Medtronic, Inc.) incorporate ventricular capture management algorithms. However, such algorithms require specific circuitry and sensing capabilities to be able to perform this function that are not currently available in the CRT products. Also, the feasibility of this technology for LV capture management has yet to be established. Note that the present invention is primarily intended for ventricular capture *verification,* and is not directed solely to ventricular capture *management,* although the benefits of the invention advantageously contribute to both capture verification and management.

A need therefore exists in the art to effectively chronically deliver ventricular pacing therapies (including CRT) to patients who might not otherwise receive the full benefit of such therapies.

SUMMARY

Among other contributions to the art, the present invention addresses the issues identified above of not providing adequate metrics (or diagnostics) to a physician regarding LV (and therefore bi-ventricular) capture. The invention addresses this significant need where capture management functionality is not available in a CRT device. According to the invention, an algorithm is described for rapid incorporation into next-generation CRT devices that actively performs LV capture verification test(s) on a daily basis. The results of the test(s) can be stored and/or provided to the user, a clinician, or

other entity. The results of the tests can be provided remotely or via a programming head at a next programmer-based session, as is known in the art. The data regarding LV capture can be used, for example, to record or demonstrate whether an intended CRT delivery is occurring and the amount of time or percentage that a patient in fact received CRT. If LV capture verification is NOT confirmed, in addition to the stored diagnostic metrics, a patient alert can be triggered to warn the patient (and/or a clinician) that the device is not functioning as intended and the patient should consider consulting a physician.

In one form of the invention, such a patent alert can be triggered on a remote patient management network (e.g., the Medtronic CareLink® remote monitoring service for patients with Medtronic cardiac devices) to notify third parties of the lack of CRT delivery. This test and the resultant diagnostic metric values (e.g., percentage of actual CRT delivery in temporal terms, by the number of cardiac cycles with and without CRT delivery, or by time of day and the like) simply and accurately depicts actual CRT delivery. The values also provide assurance to the physician, patient and/or care-giver that the device is not only pacing in both ventricular chambers, but capturing, thereby providing maximal therapeutic benefit to the patient. The values also help in the early identification of a situation where, for some reason a pacing lead is not capturing in the associated ventricle thereby minimizing patient discomfort and restoration of the desired therapeutic regime. Also, a test according to the invention can be applied to verify RV capture and for in-office, easy-to-use acute confirmation of capture verification of the LV and RV.

In addition, certain forms of the invention also provide: (1) assurance and confidence to the physician that each patient is receiving appropriate bi-ventricular pacing therapy (with capture in both chambers); (2) a means for alerting the patient and the physician on an ambulatory basis when LV capture is not verified, thereby minimizing time where patient is not optimally treated with CRT; (3) an easy to use in-office test for verifying LV/RV capture.

Some applications of the invention without limitation include: (1) ambulatory, automatic LV capture verification; (2) ambulatory, automatic RV capture verification; (3) diagnostic data display on trends of capture performance; (4) alerts to physicians and patients when LV capture is suspect; (5) in-office easy-to-use LV/RV capture verification testing; and (6) automatic ambulatory LV and RV capture management (e.g., adjustment of pacing outputs to maintain capture). The latter use can include aspects of the following:

The present inventive method provides an effective avenue for providing device intelligence and automatic adjustment of operating parameters to ensure pacing capture of the ventricles (LV and/or RV). In the event that pacing capture is lost, or is suspect, the patient or a clinic (or clinician) can be notified and/or certain pacing or sensed parameters of the medical device stored and/or sent via telemetry to a remote location for later review. The stored parameters provide a clinician with diagnostic data for a patient that can be stored in a graphical format, histogram or the like for convenient review.

According to the present invention a ventricular pacing device (including CRT delivery devices) analyzes myocardial electrogram signals in one ventricle can be used to infer capture or loss-of-capture (LOC) of an earlier stimulus pulse in the other ventricle, on a continuous (every pacing cycle), aperiodic or periodic basis. Rather than using an evoked-response principle as has been the basis of capture detection in prior art systems, a principle employed via the present invention uses evidence of inter-ventricular conduction (i.e., from the opposite chamber) as evidence of capture, since a capturing pacing stimulus will cause inter-ventricular wavefront propagation (i.e., conduction) and depolarization of the opposite chamber.

Using existing sense amplifiers and associated circuitry, simple and efficient signal analysis, and discrimination of the conducted signal of interest (from unwanted signals of cardiac activity such as T-waves, premature ventricular contractions, or "PVCs," far-field R-waves, and the like) can be enhanced as needed based on the timing the sensed signal, its magnitude or other morphology characteristics, as registered by suitable circuitry.

Ventricular sensing of intrinsic (not evoked) depolarization signal is thus used to infer LOC, as a basis for diagnostic and auto-adjustment of stimulus output, in CRT or multi-site bradycardia therapy devices.

The foregoing and other aspects and features of the present invention will be more readily understood from the following detailed description of the embodiments thereof, when considered in conjunction with the drawings, in which like reference numerals indicate similar structures throughout the several views.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of transmission of a normal cardiac conduction system through which depolarization waves are propagated through the heart in a normal intrinsic electrical activation sequence.

FIG. 2 is a schematic diagram depicting a three-channel, atrial and bi-ventricular, pacing system for implementing the present invention.

FIG. 3 is a simplified block diagram of one embodiment of IPG circuitry and associated leads employed in the system of FIG. 2 for providing three sensing channels and corresponding pacing channels that selectively functions in a ventricular pacing mode providing ventricular capture verification according to the present invention.

FIGS. 4-6 depicts flow charts setting forth embodiments of the ventricular capture verification testing according to the present invention.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

In the following detailed description, references are made to illustrative embodiments for carrying out methods of confirming pacing capture of ventricular pacing stimulation. It is understood that other embodiments may be utilized without departing from the scope of the invention. For example, the invention is disclosed in detail herein in the context of a bi-ventricular CRT delivery. In one form of the invention, a pacing regimen is modified to single-ventricle pacing therapy delivery wherein ventricular sensing in a first ventricle of a pacing stimulus delivered to a second ventricle is used to verify pacing capture in said second ventricular chamber. Thus, loss-of-capture (LOC) can be declared, verified or managed and one of several possible responses initiated. For example, the pacing pulse stimulus can be adjusted (e.g., modified pulse amplitude, pulse width, polarity, etc.), a pacing mode-switch can be implemented, and/or in relatively extreme cases a clinician can attempt to adjust the system, including electrode location, to improve pacing capture.

A cardiac pacing apparatus, according to the invention, comprises a programmable implantable pulse generator (IPG) that can be operated as a dual- or triple-chamber pacing system having an AV synchronous operating mode for restoring upper and lower heart chamber synchronization and/or right and left atrial and/or ventricular chamber depolarization synchrony. A system according to the invention efficiently provides cardiac

resynchronization therapy (CRT) with a single ventricular stimulus per cardiac cycle in a fusion-inducing CRT delivery or with a pair of synchronized bi-ventricular pacing stimulus per cardiac cycle.

The present invention provides enhanced hemodynamic performance for patients that benefit from CRT delivery due to various forms of heart failure, ventricular dysfunctions and/or ventricular conduction abnormalities. Pacing systems according to the present invention can also include rate responsive features and anti-tachyarrhythmia pacing and the like. In addition, a system according to the invention can include cardioversion and/or defibrillation therapy delivery.

In accordance with an aspect of the present invention, a method and apparatus is provided to mimic the normal depolarization-repolarization cardiac cycle sequence (nominally depicted in FIG. 1) and restore cardiac intra- and/or inter-ventricular synchrony between the RV and LV that contributes to adequate cardiac output related to the synchronized electromechanical performance of the RV and LV. The foregoing and other advantages of the invention are realized through confirmed delivery of cardiac pacing stimulation to the ventricles. For example, a number of physiologic factors can influence the ability of delivered pacing stimulus to capture a cardiac chamber. For instance, conduction delays through the A-V node and/or the His-Purkinje fibers, electrical conduction delay for sensing intra-cardiac events (from electrodes through threshold sensing circuitry of a medical device), electrical conduction delay for pacing therapy delivery circuitry, electro-mechanical delay associated with the delivery of a pace and the ensuing mechanical contraction, ischemic episodes temporarily tempering conduction pathways, myocardial infarction(s) zones, all can deleteriously impact cardiac conduction and thereby affect an operating pacing therapy delivery regime. Because the conduction status of a patient can vary over time and/or vary based on other factors such as heart rate, autonomic tone and metabolic status, the present invention provides a dynamically controllable resynchronization pacing modality.

According to the invention verification of capture can be triggered so that a desired amount of dual- or single-chamber (fusion-based) CRT delivery ensues. Some of the factors include, (i) completion of a pre-set number of cardiac cycles, (ii) pre-set time limit, (iii) loss of capture of a paced ventricle, (iv) physiologic response triggers (e.g., systemic or intra-cardiac pressure fluctuation, heart rate excursion, metabolic demand increase,

decrease in heart wall acceleration, intra-cardiac electrogram morphology or timing, etc.) and/or (v) time of day, and the like. The present invention provides a cardiac pacing system that can readily compensate for the particular implantation sites of the pace/sense electrode pair operatively coupled to a ventricular chamber. When implemented in a triple-chamber embodiment, a pacing system according to the present invention can quickly mode-switch in the event that loss-of-capture (LOC) is declared.

FIG. 2 is a schematic representation of an implanted, triple-chamber cardiac pacemaker comprising a pacemaker IPG 14 and associated leads 16,32,52 in which the present invention may be practiced. The pacemaker IPG 14 is implanted subcutaneously in a patient's body between the skin and the ribs. The three endocardial leads 16,32,52 operatively couple the IPG 14 with the RA, the RV and the LV, respectively. Each lead has at least one electrical conductor and pace/sense electrode, and a remote indifferent can electrode 20 is formed as part of the outer surface of the housing of the IPG 14. As described further below, the pace/sense electrodes and the remote indifferent can electrode 20 (IND_CAN electrode) can be selectively employed to provide a number of unipolar and bipolar pace/sense electrode combinations for pacing and sensing functions, particularly sensing far field signals (e.g. far field R-waves). The depicted positions in or about the right and left heart chambers are also merely exemplary. Moreover other leads and pace/sense electrodes may be used instead of the depicted leads and pace/sense electrodes that are adapted to be placed at electrode sites on or in or relative to the RA, LA, RV and LV. Also, as noted previously, multiple electrodes and/or leads may be deployed into operative communication with the relatively "late" depolarizing ventricle to pace at multiple sites with varying degrees of pre-excitation. In addition, mechanical and/or metabolic sensors can be deployed independent of, or in tandem with, one or more of the depicted leads. In the event that multiple pacing electrodes are operatively deployed into communication with a single chamber, a capture detection for each such electrode may be individually performed. That is, different pacing stimulus can be implemented for each discrete pacing location and said pacing stimulus delivery can thus be tuned for capture and/or conduction anomalies (e.g., due to infarct or ischemia or the like).

As depicted, a bipolar endocardial RA lead 16 passes through a vein into the RA chamber of the heart 10, and the distal end of the RA lead 16 is attached to the RA wall by an attachment mechanism 17. The bipolar endocardial RA lead 16 is formed with an in-

line connector 13 fitting into a bipolar bore of IPG connector block 12 that is coupled to a pair of electrically insulated conductors within lead body 15 and connected with distal tip RA pace/sense electrode 19 and proximal ring RA pace/sense electrode 21. Delivery of atrial pace pulses and sensing of atrial sense events is effected between the distal tip RA pace/sense electrode 19 and proximal ring RA pace/sense electrode 21, wherein the proximal ring RA pace/sense electrode 21 functions as an indifferent electrode (IND_RA). Alternatively, a unipolar endocardial RA lead could be substituted for the depicted bipolar endocardial RA lead 16 and be employed with the IND_CAN electrode 20. Or, one of the distal tip RA pace/sense electrode 19 and proximal ring RA pace/sense electrode 21 can be employed with the IND_CAN electrode 20 for unipolar pacing and/or sensing.

Bipolar, endocardial RV lead 32 is passed through the vein and the RA chamber of the heart 10 and into the RV where its distal ring and tip RV pace/sense electrodes 38 and 40 are fixed in place in the apex by a conventional distal attachment mechanism 41. The RV lead 32 is formed with an in-line connector 34 fitting into a bipolar bore of IPG connector block 12 that is coupled to a pair of electrically insulated conductors within lead body 36 and connected with distal tip RV pace/sense electrode 40 and proximal ring RV pace/sense electrode 38, wherein the proximal ring RV pace/sense electrode 38 functions as an indifferent electrode (IND_RV). Alternatively, a unipolar endocardial RV lead could be substituted for the depicted bipolar endocardial RV lead 32 and be employed with the IND_CAN electrode 20. Or, one of the distal tip RV pace/sense electrode 40 and proximal ring RV pace/sense electrode 38 can be employed with the IND_CAN electrode 20 for unipolar pacing and/or sensing.

Further referring to FIG. 2, a bipolar, endocardial coronary sinus (CS) lead 52 is passed through a vein and the RA chamber of the heart 10, into the coronary sinus and then inferiorly in a branching vessel of the great cardiac vein to extend the proximal and distal LV CS pace/sense electrodes 48 and 50 alongside the LV chamber. The distal end of such a CS lead is advanced through the superior vena cava, the right atrium, the ostium of the coronary sinus, the coronary sinus, and into a coronary vein descending from the coronary sinus, such as the lateral or posteriolateral vein. In addition, while not depicted in FIG. 2 the atrial, ventricular, and/or CS-deployed pacing leads can couple to the exterior of a heart via a pericardial or epicardial attachment mechanism.

In a four chamber or channel embodiment, LV CS lead 52 bears proximal LA CS pace/sense electrodes 28 and 30 positioned along the CS lead body to lie in the larger diameter CS adjacent the LA. Typically, LV CS leads and LA CS leads do not employ any fixation mechanism and instead rely on the close confinement within these vessels to maintain the pace/sense electrode or electrodes at a desired site. The LV CS lead 52 is formed with a multiple conductor lead body 56 coupled at the proximal end connector 54 fitting into a bore of IPG connector block 12. A small diameter lead body 56 is selected in order to lodge the distal LV CS pace/sense electrode 50 deeply in a vein branching from the great vein (GV).

In this case, the CS lead body 56 would encase four electrically insulated lead conductors extending proximally from the more proximal LA CS pace/sense electrode(s) and terminating in a dual bipolar connector 54. The LV CS lead body would be smaller between the LA CS pace/sense electrodes 28 and 30 and the LV CS pace/sense electrodes 48 and 50. It will be understood that LV CS lead 52 could bear a single LA CS pace/sense electrode 28 and/or a single LV CS pace/sense electrode 50 that are paired with the IND_CAN electrode 20 or the ring electrodes 21 and 38, respectively for pacing and sensing in the LA and LV, respectively.

In this regard, FIG. 3 depicts bipolar RA lead 16, bipolar RV lead 32, and bipolar LV CS lead 52 without the LA CS pace/sense electrodes 28 and 30 coupled with an IPG circuit 300 having programmable modes and parameters of a bi-ventricular DDD/R type known in the pacing art. In turn the sensor signal processing circuit 43 indirectly couples to the timing circuit 330 and via bus 306 to microcomputer circuitry 302. The IPG circuit 300 is illustrated in a functional block diagram divided generally into a microcomputer circuit 302 and a pacing circuit 320. The pacing circuit 320 includes the digital controller/timer circuit 330, the output amplifiers circuit 340, the sense amplifiers circuit 360, the RF telemetry transceiver 322, the activity sensor circuit 322 as well as a number of other circuits and components described below.

Crystal oscillator circuit 338 provides the basic timing clock for the pacing circuit 320, while battery 318 provides power. Power-on-reset circuit 336 responds to initial connection of the circuit to the battery for defining an initial operating condition and similarly, resets the operative state of the device in response to detection of a low battery condition. Reference mode circuit 326 generates stable voltage reference and currents for

the analog circuits within the pacing circuit 320, while analog to digital converter ADC and multiplexer circuit 328 digitizes analog signals and voltage to provide real time telemetry if a cardiac signals from sense amplifiers 360, for uplink transmission via RF transmitter and receiver circuit 332. Voltage reference and bias circuit 326, ADC and multiplexer 328, power-on-reset circuit 336 and crystal oscillator circuit 338 may correspond to any of those presently used in current marketed implantable cardiac pacemakers.

If the IPG is programmed to a rate responsive mode, the signals output by one or more physiologic sensor are employed as a rate control parameter (RCP) to derive a physiologic escape interval. For example, the escape interval is adjusted proportionally the patient's activity level developed in the patient activity sensor (PAS) circuit 322 in the depicted, exemplary IPG circuit 300. The patient activity sensor 316 is coupled to the IPG housing and may take the form of a piezoelectric crystal transducer as is well known in the art and its output signal is processed and used as the RCP. Sensor 316 generates electrical signals in response to sensed physical activity that are processed by activity circuit 322 and provided to digital controller/timer circuit 330. Activity circuit 332 and associated sensor 316 may correspond to the circuitry disclosed in U.S. Patent Nos. 5,052,388 and 4,428,378. Similarly, the present invention may be practiced in conjunction with alternate types of sensors such as oxygenation sensors, pressure sensors, pH sensors and respiration sensors, all well known for use in providing rate responsive pacing capabilities. Alternately, QT time may be used as the rate indicating parameter, in which case no extra sensor is required. Similarly, the present invention may also be practiced in non-rate responsive pacemakers.

Data transmission to and from the external programmer is accomplished by means of the telemetry antenna 334 and an associated RF transceiver 332, which serves both to demodulate received downlink telemetry and to transmit uplink telemetry. Uplink telemetry capabilities will typically include the ability to transmit stored digital information, e.g. operating modes and parameters, EGM histograms, and other events, as well as real time EGMs of atrial and/or ventricular electrical activity and Marker Channel pulses indicating the occurrence of sensed and paced depolarizations in the atrium and ventricle, as are well known in the pacing art.

Microcomputer 302 contains a microprocessor 304 and associated system clock 308 and on-processor RAM and ROM chips 310 and 312, respectively. In addition, microcomputer circuit 302 includes a separate RAM/ROM chip 314 to provide additional memory capacity. Microprocessor 304 normally operates in a reduced power consumption mode and is interrupt driven. Microprocessor 304 is awakened in response to defined interrupt events, which may include A-TRIG, RV-TRIG, LV-TRIG signals generated by timers in digital timer/controller circuit 330 and A-EVENT, RV-EVENT, and LV-EVENT signals generated by sense amplifiers circuit 360, among others. The specific values of the intervals and delays timed out by digital controller/timer circuit 330 are controlled by the microcomputer circuit 302 by means of data and control bus 306 from programmed-in parameter values and operating modes. In addition, if programmed to operate as a rate responsive pacemaker, a timed interrupt, e.g., every cycle or every two seconds, may be provided in order to allow the microprocessor to analyze the activity sensor data and update the basic A-A, V-A, or V-V escape interval, as applicable. In addition, the microprocessor 304 may also serve to define variable, operative AV delay intervals and the energy delivered to each ventricle.

In one embodiment of the invention, microprocessor 304 is a custom microprocessor adapted to fetch and execute instructions stored in RAM/ROM unit 314 in a conventional manner. It is contemplated, however, that other implementations may be suitable to practice the present invention. For example, an off-the-shelf, commercially available microprocessor or microcontroller, or custom application-specific, hardwired logic, or state-machine type circuit may perform the functions of microprocessor 304.

Digital controller/timer circuit 330 operates under the general control of the microcomputer 302 to control timing and other functions within the pacing circuit 320 and includes a set of timing and associated logic circuits of which certain ones pertinent to the present invention are depicted. The depicted timing circuits include URI/LRI timers 364, V-V delay timer 366, intrinsic interval timers 368 for timing elapsed V-EVENT to V-EVENT intervals or V-EVENT to A-EVENT intervals or the V-V conduction interval, escape interval timers 370 for timing A-A, V-A, and/or V-V pacing escape intervals, an AV delay interval timer 372 for timing the A-LVp delay (or A-RVp delay) from a preceding A-EVENT or A-TRIG, a post-ventricular timer 374 for timing post-ventricular time periods, and a date/time clock 376.

According to the invention, the AV delay interval timer 372 is loaded with an appropriate delay interval for one ventricular chamber (i.e., either an A-RVp delay or an A-LVp delay as determined by the flow chart depicted at FIG. 4 and FIG. 5) to time-out starting from a preceding A-PACE or A-EVENT. The interval timer 372 triggers pacing stimulus delivery, and can based on one or more prior cardiac cycles (or from a data set empirically derived for a given patient)

The post-event timers 374 time out the post-ventricular time periods following an RV-EVENT or LV-EVENT or a RV-TRIG or LV-TRIG and post-atrial time periods following an A-EVENT or A-TRIG. The durations of the post-event time periods may also be selected as programmable parameters stored in the microcomputer 302. The post-ventricular time periods include the PVARP, a post-atrial ventricular blanking period (PAVBP), a ventricular blanking period (VBP), a post-ventricular atrial blanking period (PVARP) and a ventricular refractory period (VRP) although other periods can be suitably defined depending, at least in part, on the operative circuitry employed in the pacing engine. The post-atrial time periods include an atrial refractory period (ARP) during which an A-EVENT is ignored for the purpose of resetting any AV delay, and an atrial blanking period (ABP) during which atrial sensing is disabled. It should be noted that the starting of the post-atrial time periods and the AV delays can be commenced substantially simultaneously with the start or end of each A-EVENT or A-TRIG or, in the latter case, upon the end of the A-PACE which may follow the A-TRIG. Similarly, the starting of the post-ventricular time periods and the V-A escape interval can be commenced substantially simultaneously with the start or end of the V-EVENT or V-TRIG or, in the latter case, upon the end of the V-PACE which may follow the V-TRIG. The microprocessor 304 also optionally calculates AV delays, post-ventricular time periods, and post-atrial time periods that vary with the sensor based escape interval established in response to the RCP(s) and/or with the intrinsic atrial rate.

The output amplifiers circuit 340 contains a RA pace pulse generator (and a LA pace pulse generator if LA pacing is provided), a RV pace pulse generator, and a LV pace pulse generator or corresponding to any of those presently employed in commercially marketed cardiac pacemakers providing atrial and ventricular pacing. In order to trigger generation of an RV-PACE or LV-PACE pulse, digital controller/timer circuit 330 generates the RV-TRIG signal at the time-out of the A-RVp delay (in the case of RV pre-

excitation) or the LV-TRIG at the time-out of the A-LVp delay (in the case of LV pre-excitation) provided by AV delay interval timer 372 (or the V-V delay timer 366). Similarly, digital controller/timer circuit 330 generates an RA-TRIG signal that triggers output of an RA-PACE pulse (or an LA-TRIG signal that triggers output of an LA-PACE pulse, if provided) at the end of the V-A escape interval timed by escape interval timers 370.

The output amplifiers circuit 340 includes switching circuits for coupling selected pace electrode pairs from among the lead conductors and the IND_CAN electrode 20 to the RA pace pulse generator (and LA pace pulse generator if provided), RV pace pulse generator and LV pace pulse generator. Pace/sense electrode pair selection and control circuit 350 selects lead conductors and associated pace electrode pairs to be coupled with the atrial and ventricular output amplifiers within output amplifiers circuit 340 for accomplishing RA, LA, RV and LV pacing.

The sense amplifiers circuit 360 contains sense amplifiers corresponding to any of those presently employed in contemporary cardiac pacemakers for atrial and ventricular pacing and sensing. As noted in the above-referenced, commonly assigned, '324 patent, it has been common in the prior art to use very high impedance P-wave and R-wave sense amplifiers to amplify the voltage difference signal which is generated across the sense electrode pairs by the passage of cardiac depolarization wavefronts. The high impedance sense amplifiers use high gain to amplify the low amplitude signals and rely on pass band filters, time domain filtering and amplitude threshold comparison to discriminate a P-wave or R-wave from background electrical noise. Digital controller/timer circuit 330 controls sensitivity settings of the atrial and ventricular sense amplifiers 360.

The sense amplifiers are typically uncoupled from the sense electrodes during the blanking periods before, during, and after delivery of a pace pulse to any of the pace electrodes of the pacing system to avoid saturation of the sense amplifiers. The sense amplifiers circuit 360 includes blanking circuits for uncoupling the selected pairs of the lead conductors and the IND_CAN electrode 20 from the inputs of the RA sense amplifier (and LA sense amplifier if provided), RV sense amplifier and LV sense amplifier during the ABP, PVABP and VBP. The sense amplifiers circuit 360 also includes switching circuits for coupling selected sense electrode lead conductors and the IND_CAN electrode 20 to the RA sense amplifier (and LA sense amplifier if provided), RV sense amplifier and

LV sense amplifier. Again, sense electrode selection and control circuit 350 selects conductors and associated sense electrode pairs to be coupled with the atrial and ventricular sense amplifiers within the output amplifiers circuit 340 and sense amplifiers circuit 360 for accomplishing RA, LA, RV and LV sensing along desired unipolar and bipolar sensing vectors.

Right atrial depolarizations or P-waves in the RA-SENSE signal that are sensed by the RA sense amplifier result in a RA-EVENT signal that is communicated to the digital controller/timer circuit 330. Similarly, left atrial depolarizations or P-waves in the LA-SENSE signal that are sensed by the LA sense amplifier, if provided, result in a LA-EVENT signal that is communicated to the digital controller/timer circuit 330. Ventricular depolarizations or R-waves in the RV-SENSE signal are sensed by a ventricular sense amplifier result in an RV-EVENT signal that is communicated to the digital controller/timer circuit 330. Similarly, ventricular depolarizations or R-waves in the LV-SENSE signal are sensed by a ventricular sense amplifier result in an LV-EVENT signal that is communicated to the digital controller/timer circuit 330. The RV-EVENT, LV-EVENT, and RA-EVENT, LA-SENSE signals may be refractory or non-refractory, and can inadvertently be triggered by electrical noise signals or aberrantly conducted depolarization waves rather than true R-waves or P-waves.

To simplify the description of FIG. 4, it will be assumed that the following references to an "A-EVENT" and "A-PACE" will denote right atrial activity. In the event that the left atrium is monitored (or stimulated), the reader should appreciate that the LA is referred to.

An operating mode 400 of IPG circuit 300 according to the present invention are depicted in the flow chart (FIG. 4) and described as follows. At decision step 402 a nominal ventricular capture test initiation trigger is implemented. Although as depicted the decision relates to a time of day (i.e., 3:00 a.m.) decision step 402 can include any of a wide variety of temporal or event-based triggers. If the criteria at step 402 is not met then the process continues to step 404 and no action is taken. If the decision is affirmative at step 402 then decision step 406 is implemented wherein any of a variety of criteria for not proceeding with the conduction test 400 are analyzed. If the designated criteria are met then the test 400 does not proceed (at step 408). Representative criteria includes the presence of an arrhythmia, high heart rate, high activity sensor signal input, and the like. If

the designated criteria is met then the test 400 proceeds (at step 410) by programming a relatively long A-V delay interval so that the patient's PR interval (i.e., A-event to ventricular depolarization) emerges. The measured PR interval is stored in a computer memory or the like.

Then at step 412 the pacing therapy mode-switches to (or implements) a single ventricular pacing therapy with a relatively short (or minimum) A-V delay interval for at least one cardiac cycle. Then at step 414 if no ventricular sense event (R-sense) occurs in the non-paced ventricle prior to a next-scheduled pacing stimulus delivery, then the method 400 proceeds to step 416 wherein the result of step 414 is evaluated to see if this is the first such event in the recent past (e.g., on a given day, within a temporal window, more than once, etc.) which if positive the method 400 returns to step 412. If the lack of a V-sense event is not the first occurrence in a given day, for example, then the method 400 proceed to step 424 wherein the pacing therapy delivery is labeled as loss-of-capture (LOC) before proceeding to step 434, ending the method 400 until a later iteration occurs.

Following a positive result from decision step 414 the method 400 proceeds to decision step 418 wherein the temporal location of the R-sense event is evaluated whether or not it occurred earlier than a short discrimination interval of the patient's PR interval (e.g., earlier than about 40 ms less than the PR measured interval) is considered. In the event that the V-sense event occurs earlier than a physiologically short period of time before the expiration of the patient's PR interval then at step 420 the V-sensed event is queried whether it was the first such event in the recent past (e.g., on a given day, etc.) and if answered in the affirmative then the method 400 returns to step 412 – as described herein. If not, then the pacing regimen is declared as pacing "capture verified" (or equivalent) at step 432.

However, in the event that the V-sense event occurs later than the physiologically short period of time before the expiration of the patient's PR interval then the method 400 proceeds to step 422 and the V-sensed event is queried whether it was the first such event in the recent past (e.g., on a given day, etc.) and if answered in the affirmative then the method 400 returns to step 412 – as described herein. If answered in the negative then the method 400 proceeds to step 426 where the R-sense event is compared to a typical physiologic ventricular depolarization following an A-event (e.g., did the V-sense event register at a moment greater than about 310 ms following the A-event). If step 426 is

answered in the affirmative then a pacing regimen LOC is declared at step 428 and the method 400 ends at step 434. If step 426 is answered in the negative then the pacing regimen is classified as likely not valid (e.g., "capture suspect" or equivalent) and an optional message logged (at step 430) that the patient's, or device, history merits review and then the method 400 ends at step 434 until the method is later invoked to verify whether ventricular pacing stimuli captures as intended.

The particular operating mode of the present invention is a programmed or hard-wired sub-set of possible CRT delivery operating modes, including bi-ventricular pacing whether involving simultaneous V-V pacing stimulation (i.e., synchronized ventricular pacing therapy delivery) or sequential V-V pacing stimulation (e.g., in an attempt to compensate for various cardiac conduction and/or contractile defects). In addition, the invention can be used to verify pacing capture of either one of an RV or an LV (and RA and LA). As noted, the inventive algorithm advantageously helps confirm the capture status of a pacing regimen by providing one of: a LOC signal, a capture signal, or a "capture suspect" signal. Of course, the methods according to the present invention are intended to be stored as executable instructions on any appropriate computer readable medium that provides control signals to effect the technical result of the invention herein described and depicted, although certain of the steps of the inventive methods may be performed manually as well.

The presently described and depicted embodiment of the invention relies on two occurrences of the presence of absence or specific timing of the RV sense in order to render a determination, in order to prevent an incorrect determination that may result from a PVC or conducted PAC or the like. In other forms of the invention the results could rely on a single cycle or use a voting scheme that relies on more than 2 cycles to confirm results.

In the presently described and depicted embodiment of the invention capture verification testing occurs on a daily basis, however, the testing may occur based on a triggering signal (e.g., from a patient or clinician, from a hand-held programmer or the like locally or remotely spaced from said patient). Upon confirmation of capture of a cardiac chamber, a desired pacing therapy delivery can be re-enabled and continue until: a loss of capture occurs, a predetermined period of time elapses, a mode-switch occurs to another pacing regimen (e.g., due to a automated physiologic trigger, a programming change, etc.)

or the like. If a loss of capture in a ventricular chamber is detected it could indicate one or more possible problems requiring remedial action. For example, the pacing electrodes might have malfunctioned or become dislodged, an elongated conductor within a medical electrical lead might have been damaged, open- or short-circuited. Accordingly, in addition to verifying pacing capture, the present invention optionally includes capability for alerting a physician, clinician, patient, health care provider or the like that pacing system interrogation might be required. In addition, the configuration of the pacing system, including collected patient data and physiologic parameters can be stored for later retrieval thereby enhancing the likelihood of an accurate assessment of the operating condition of the pacing system.

In one form of the invention, following detection of inappropriate or non-programmed operating conditions (e.g., including receipt of a LOC signal during CRT delivery) the pacing therapy can be adjusted, discontinued or a mode switch performed to another pacing modality which, for example might exclude the pacing lead that produced the LOC signal. One aspect of this form of the invention, upon receipt of a ventricular LOC signal an intended bi-ventricular or uni-ventricular CRT delivery regimen is suspended and an atrial-pacing only therapy is implemented (e.g., an AAI, ADI, AAI/R, ADI/R and the like). That is, assuming that a patient's A-V conduction remains relatively intact until such time as the patient is able to receive qualified medical attention or until a subsequent ventricular capture verification test indicates that non-suspect capture has been achieved. In this regard, U.S. Pat. No. 6,772,005 to Casavant et al. entitled "Preferred ADI/R: a Permanent Pacing Mode to Eliminate Ventricular Pacing While Maintaining Backup Support" which is assigned to Medtronic, Inc. is hereby incorporated herein by reference in its entirety.

In a yet another related embodiment of the foregoing aspect of the invention, in the event that a ventricular LOC signal persists a mode-switch from a bi-ventricular CRT to a uni-ventricular, fusion-based CRT can occur. In particular if the LOC signal relates to a heart failure patient's first-to-depolarize ventricle such a uni-ventricular, fusion-based CRT delivery regimen characterized by pre-excitation of the second-to-depolarize ventricle can be chronically implemented. In this regard pending non-provisional U.S. patent application no. 10/803,570 filed 17 March 2004 by J. Burnes and T. Mullen (Atty. Dkt. P-11471.00) and entitled "APPARATUS AND METHODS OF ENERGY

EFFICIENT, ATRIAL-BASED BI-VENTRICULAR FUSION-PACING" is hereby incorporated herein by reference in its entirety.

Now turning to FIG. 5, another embodiment of a method according to the present invention is depicted as method 500. To begin process 500, one of the steps 424,428, and optionally 430 of method 400 are declared in the affirmative as just described. Then, at 502 the intrinsic conduction (e.g., A-V conduction) is checked to ensure that the intrinsic conduction is intact. If the A-V conduction is deemed not present then at step 504 one of a variety of steps can be taken. For example, at step 504 an alert can be issued (e.g., to a care giver, a patient, a clinic, etc.), a dual-chamber pacing regimen can be implement in lieu of CRT delivery, a set of then-current pacing parameters, pacing performance metrics and patient responses can be stored in a memory structure, and the like. On the other hand, it adequate A-V conduction is deemed present then at step 506 the pacing regimen is switched to one of: an AAI modality, an AAI/R modality, a ADI modality, a AAI/R modality, a RV- or LV-only fusion-based pacing therapy. For the later two modalities, the conduction check at step 502 could optionally determine whether one of the ventricles is depolarizing and/or contracting later than the other. Then, assuming no LOC signal was received for the later-activating ventricle then the uni-ventricular, fusion-based pacing can be beneficially delivered using the ventricular chamber having no LOC signal.

In FIG. 6, a process 600 illustrating another embodiment of a method according to the present invention is depicted as method 600. To begin process 600, most of the steps of method 400 are implemented (i.e., steps 406-422, 432, and 434) and if one of step 424, 428 and optionally 430 of method 400 are declared in the affirmative then at step 602 at least one characteristic of the pacing pulse energy is adjusted to enhance the likelihood of avoiding a declaration of LOC or "suspect capture." That is, in most instances at least one of a pulse width, a pulse amplitude, a frequency, and a pulse polarity is adjusted to increase the magnitude thereof. The adjustment can be iterative in either the increasing or decreasing directions. Then, the steps of method 400 previously implemented (steps 406-422, 432, and 434) until no LOC signals are received. Then, at step 604 a CRT delivery can resume with optional re-check of ventricular capture at step 606.

In the event that at steps 424, 428 and 430 a LOC signal is received after one or more attempt to adjust the pacing pulse delivery characteristics (at step 602) then the processes defined at step 504 can be implemented in lieu of continuing adjustment of the pacing

pulse delivery characteristics. That is, as noted above at step 504 an alert can be issued (e.g., to a care giver, a patient, a clinic, etc.), a dual-chamber pacing regimen can be implement in lieu of CRT delivery, a set of then-current pacing parameters, pacing performance metrics and patient responses can be stored in a memory structure, and the like.

The patient may, in the best scenario, be relieved of pacing therapy delivery altogether (programming the pacing circuitry to an ODO monitoring-only "pacing modality"). Assuming the patient is not chronotropically incompetent, normal sinus rhythm may emerge permanently for all the activities of daily living. Additionally, the process 600 may be employed to search for a change in conduction status (e.g., wherein a later-to-depolarize ventricle changes from the LV to the RV).

A few salient features of the automatic, ambulatory LV/RV capture verification test according to the invention are described below:

(1) The feature (e.g., "Automatic LV/RV Capture Verification") will be selectably programmable by the user and no other programmable parameters associated with the conduction test sequences.

(2) A "patient alert" type selection can be optionally provided (selectable on or off) associated with the results of the LV/RV Capture Verification test sequences. Such an alert feature includes a range of selectable options regarding when to sound the alert (e.g., immediately after a negative test, based on diurnal cycles such as in the morning or upon detection of patient activity after a lengthy sedentary period, etc.) are within the purview of the invention.

(3) In one form of the invention, the conduction test sequences are applied at approximately the same (whether on a daily-, weekly-, monthly-basis, etc.) for example at night when the patient is sleeping. For the example described, the tests are applied at 3:00 a.m.

(4) The conduction test sequence with generally be withheld in the event that the patient's then-current heart rhythm supports running the test (e.g., no atrial or ventricular tachycardia episodes in progress at the time when the test starts or while the test sequences are running, the atrial rate is relatively low, and the patient is currently paced in the ventricle).

(5) For example, every night at approximately 3:00 a.m. the device initiates the conduction test sequence. The first step is to measure the time interval between an atrial event to an antegrade-conducted RV sense (referred to as "PR interval" herein). This is done by setting a relatively long AV interval (e.g., 400 ms) for one cardiac cycle and measuring the time between said A-event and the associated v-event (i.e., an RV sensed event). If a ventricular pace (VP) occurs, it indicates that the patient likely has some degree of AV block. The PR interval used for an algorithm according to the invention (see below) will be set to the programmed AV interval in this case.

(6) The device is then programmed to LV-only pacing for one cardiac cycle with a relatively short, or minimum, AV interval. Then, one of the following two results are obtained, with the concomitant response(s).

a. No sense RV-event: If an RV-event is not sensed prior to the next scheduled ventricular pace (VP), it implies "loss of capture" (LOC) because there is no conduction from the LV paced event to the RV - assuming that RV sensing components and circuitry are not an issue. For completeness, other cardiac pacing system features are available and will be provided to alert the clinician to this possibility (but such features are not relevant to the present invention). However, the inventors posit that there exists a rare possibility that a premature ventricular contraction (PVC) may have occurred around the time of the LV pace event (pacing stimulus delivery to the LV) in which case no RV sense event can occur due to the LV pace event (and, in particular, the associated sensing-channel blanking typically imposed upon delivery of the LV pacing stimulus). To address this unlikely situation step (6) is again performed. If an RV sense event is still not recorded, then a "loss of capture" (LOC) output signal is issued as the test result. If an RV-sense event is recorded, then the method proceeds to option b. (immediately below).

b.) RV sense event recorded: If an RV sense event is recorded prior to the next LV pace, it could mean that it came from (A) an intrinsically-conducted PR interval (from an A-event), or (B) a conducted *inter-ventricular event* (i.e., a conducted LV pace event that conducts to the RV), or (C) a PVC.

i.) Criteria for recording a relatively 'early' RV sense event: If the time interval from an A-event to an RV-sense event (referred to herein as a "Test PR") is less than or equal to the PR Interval less about 40 milliseconds (i.e., PR Interval – 40 ms), then the event could either represent scenario (B) or (C) above. In this situation, step (6) is

again repeated. If the just-described pattern manifests itself again, then ventricular pacing capture is verified (i.e., case (B) is confirmed). Such a verification and confirmation appears reasonable because the likelihood that a PVC might occur again at the same exact time interval is highly unlikely and can be safely ignored. However, if the pattern is *not* repeated again, then the prior RV-sensed event in fact represents a PVC and the current A event to RV sense interval requires attention by applying the following criteria and steps.

ii.) Criteria for recording of an "on time" RV sense event: If an RV sense event is recorded prior to the next LV pace (on the same cardiac cycle) and the Test PR interval is greater than the PR Interval less 40 milliseconds (i.e., PR Interval - 40 ms), then the RV sense event comprises either: (A) a situation wherein the LV has lost pacing capture (LOC) or (A') where the LV-RV inter-ventricular interval is greater than the PR interval or (B) a situation wherein the LV-RV inter-ventricular interval is approximately the same as the PR interval. Since the inventors recognize that empirically (i.e., from data gathered from the 500+ patient MIRACLE ICD trial) data has shown that interventricular intervals (e.g., LVP to RVS interval) times are rarely, if ever, greater than about 280 milliseconds.

Applying these values, then in the event that the Test PR is greater than 310 ms (i.e., equal to the programmed AV delay interval plus the LVP-RVS interventricular conduction time), then the result of the conduction test is a "loss of capture" (LOC) conclusion.

Conversely, if the Test PR is less than or equal to 310 milliseconds then the results of the conduction test is a "capture is suspect." Both the PR Interval and the Test PR Interval are then optionally stored into a histogram, a trend log or the like.

(7) If the result of the conduction test sequence is "capture is suspect," then the recent or previous recorded history of the patient can be used to determine if the loss of capture (LOC) result is more or less likely. Accordingly, if ventricular capture has been verified in the *recent* past (e.g., hours, days, weeks, etc.) and the presently applied Test PR Interval is much larger than previous Test PR Interval (e.g., on the order of about 60 ms or so, then "loss of capture" (LOC) is the result of the conduction test sequence.

(8) If a patient alert feature has been programmed to issue upon an LOC result, then an alert will be sounded at the programmed time. Such a patient alert can comprise any of a variety of apparatus and circuitry intended to gain the attention of a patient. Some

examples include a haptic or vibratory alert wherein a crystal or other structure disposed within an implantable medical device oscillates or moves, an audible alert, and/or activation of visual cues signaling an alert event. The alert message can be sent wirelessly to remote stations or adjacent hardware so that the patient and/or other personnel also receive the alert message.

(9) the foregoing steps (5) through (7) can be repeated every night or on an otherwise periodic or aperiodic basis.

Some of the key elements of the inventive algorithm just described are depicted and described with reference to an exemplary embodiment shown in the flowcharts appended hereto (e.g., FIGS. 4, 5 and 6). The exemplary embodiment illustrates LV capture verification. Of course, a similar flowchart also applies for RV capture verification (e.g., by switching to RV-only pacing in lieu of LV-only pacing) and can be applied for at least one cardiac cycle. The inventive conduction test sequence can be run during atrial overdrive pacing. Such overdrive pacing is known in the art and results in an increase of the length of the interval between a preceding A-event and an associated, conducted V-sense event.

In addition, a programmable bi-ventricular parameter defining V-V conduction time can be supplied to and used by the inventive algorithm. Such a conduction time can be set to a worst-case default value (e.g., 280 ms), and thereafter be user-adjusted or programmable by the user or clinician to render the test results more determinate for patients with relatively "shorter" PR intervals and relatively "longer" V-V intervals.

Devices incorporating the methods according to the invention can advantageously store and display trend, histogram and/or other information regarding capture verification tests, failing test results and results for the last few months and other data related thereto. When such data is displayed in a histogram format a clinician or patient can perhaps more readily comprehend the meaning of the data, so this type of display is favored, especially for patient display. This data would be transmitted over a hospital-, clinic-, and/or patient-adapted information network (e.g., such as the Medtronic CareLink™ Information Network by Medtronic, Inc.) with triggers and alerts triggered by 'Capture Verification Suspect" and LOC results to alert one or more clinicians viewing the patient data remotely.

The same algorithm can be adapted slightly and advantageously applied for easy-to-use in and a clinic or physician office to verify LV and RV capture or to facilitate

ambulatory LV and RV capture management (e.g., if ventricular capture is deemed to be "lost," the same algorithm is then applied at different pacing output strength to automatically determine, and program, a new pacing output at which assures ventricular pacing capture).

In summary, some of the features and benefits of the present invention include, without limitation, the following: (1) Ambulatory, automatic LV and RV capture verification; (2) Diagnostic data storing and/or displaying trends of capture performance over time; (3) Alerts and messages to physicians, care giving entities, and patients when LV/RV capture is suspect, including data related thereto; (4) In-office easy-to-use LV/RV capture verification testing; (5) Ambulatory, automatic LV and RV capture management (e.g., adjustment of pacing pulse stimulus parameters to confirm, ensure and/or regain capture); and (6) Pacing regimen mode-switching based on receipt of LOC signal, "capture suspect" signal, and capture verified signal.

It should be understood that, certain of the above-described structures, functions and operations of the pacing systems of the illustrated embodiments are not necessary to practice the present invention and are included in the description simply for completeness of an exemplary embodiment or embodiments. It will also be understood that there may be other structures, functions and operations ancillary to the typical operation of an implantable pulse generator that are not disclosed and are not necessary to the practice of the present invention. In addition, it will be understood that specifically described structures, functions and operations set forth in the above-referenced patents can be practiced in conjunction with the present invention, but they are not essential to its practice. It is therefore to be understood, that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described without actually departing from the spirit and scope of the present invention.

CLAIMS

1. A method of monitoring ventricular capture in a ventricular cardiac resynchronization therapy (CRT) delivery device to promote mechanical synchrony between ventricular chambers, comprising:

suspending a CRT delivery regimen;

verifying an absence of possibly deleterious cardiac rhythms, and after successfully verifying the absence of possibly deleterious cardiac rhythms;

conducting a ventricular conduction test to a first ventricle, wherein the first ventricle receives pacing stimulation;

monitoring a second ventricle during a period of time following , wherein said second ventricle is free of direct pacing stimulation, for inter-ventricular conduction of said pacing stimulation from said first ventricle.

2. A method according to claim 1 wherein said ventricular conduction test comprises:

extending a cardiac pacing atrio-ventricular (AV) interval;

measuring a PR time interval, said interval defined as the time elapsed between a sensed or paced atrial event (A-event) and an antegrade-conducted right ventricular sense (RVs) event, or, in the event that a ventricular pace occurs upon the expiration of the extended AV interval, assuming the presence of some degree of AV block and between said A-event and the ventricular pace, and

programming one of a relatively short AV interval and a minimum AV interval as the test AV interval.

3. A method according to claim 2, further comprising:

delivering a left ventricle-only pacing stimulus (LVp) and in the event that no right ventricular sense (RVs) event occurs prior to delivery of a next-scheduled right ventricular pace (RVp) declaring loss of capture (LOC) of said LV chamber.

4. A method according to claim 3, comprising repeating the step recited in claim 3 and in the event that LOC is again declared,

confirming the initial declaration of LV LOC.

5. A method according to claim 4, further comprising:
issuing an output signal reflecting the LV LOC declaration.

6. A method according to claim 5, wherein said output signal is stored within a memory structure.

7. A method according to claim 5, wherein said output signal is provided wirelessly to one of a cardiac device programming apparatus and a remote work station.

8. A method according to claim 7, wherein said remote work station comprises one of a patient monitor, a clinician transceiver, a processor-controlled device coupled to a patient information network.

9. A method according to claim 8, wherein said patient monitor comprises means for alerting said patient to the results of at least one of the parameters of said ventricular capture monitoring method.

10. A method according to claim 9, wherein the at least one of the parameters comprises: a test AV interval, a PR interval, a set of temporal pacing parameters, a pacing stimulation metric; a heart rate, an activity rate, a metabolic state, a presence of an ischemia episode, a presence of pulmonary edema.

11. A method according to claim 10, wherein the pacing stimulation metrics comprises at least one of: an SAV interval, a PAV interval, a pulse width, a pulse amplitude, a polarity characteristic.

12. A method according to claim 1, wherein said possibly deleterious cardiac rhythms comprise at least one of the group:
a premature ventricular contraction (PVC),
a premature atrial contraction (PAC),
an episode of supra-ventricular tachycardia (SVT),
an episode of ventricular tachycardia (VT),

an episode of ventricular fibrillation (VF),

an episode of pulsus alternans,

an episode of acute ischemia,

an episode of pulmonary edema,

a detected intrinsic heart rate exceeding a predetermined threshold,

a paced heart rate exceeding a predetermined threshold,

an activity sensor output exceeding a predetermined threshold,

an estimated pulmonary arterial diastolic (ePAD) pressure exceeding a predetermined upper threshold,

an estimated pulmonary arterial diastolic (ePAD) pressure exceeding a predetermined lower threshold,

an episode of heart failure decompensation,

an episode of hypertension,

a patient-activated testing abort signal.

13. A method according to claim 12, further comprising:

distinguishing between an intrinsically-conducted (PR) event, a conducted intra-ventricular event, a conducted inter-ventricular event, and a PVC.

14. A method according to claim 2, further comprising:

delivering a left ventricle-only pacing stimulus (LVp) and in the event that an RVs event occurs more than 40ms prior to the measured PR interval declaring capture of said LV.

15. A method according to claim 14, further comprising:

determining whether the RVs event occurred relatively early by applying pre-selected criteria; and

declaring positive detection of one of a conducted intra-ventricular event and a premature ventricular contraction (PVC).

16. A method according to claim 15, wherein the preselected criteria comprises:

setting the test AV interval to the measured PR interval minus approximately 40 ms;

repeating the steps of the method and if the Vs event occurs, confirming pacing capture of the LV.

17. A method according to claim 14, comprising repeating the step recited in claim 14 and in the event that capture is again declared,
confirming the initial declaration of LV capture.

18. A method according to claim 14, and in the event that
LOC is declared, further comprising:
repeating said ventricular capture testing method by delivering an increased pacing pulse energy and/or in an alternative polarity.

19. A method according to claim 14, and in the event that
LOC is declared, further comprising:
switching to and delivering one of: an atrial-biased, minimal ventricular pacing therapy and a uni-ventricular, fusion-based pacing therapy.

20. An apparatus for monitoring ventricular capture in a ventricular cardiac resynchronization therapy (CRT) delivery device to promote mechanical synchrony between ventricular chambers, comprising:
means for suspending a CRT delivery regimen;
means for verifying an absence of possibly deleterious cardiac rhythms;
means for conducting a ventricular conduction test wherein a first ventricle receives pacing stimulation and a second ventricle is monitored for inter-ventricular conduction of said pacing stimulation to said first ventricle after successfully verifying the absence of possibly deleterious cardiac rhythms; and
means for monitoring a second ventricle during a subsequent period of time, wherein said second ventricle is free of direct pacing stimulation, for inter-ventricular conduction of said pacing stimulation from said first ventricle.

21. An apparatus according to claim 20, wherein said ventricular conduction test further comprises:

means for extending a cardiac pacing atrio-ventricular (AV) interval;

means for measuring a PR time interval, said interval defined as the time elapsed between a sensed or paced atrial event (A-event) and an antegrade-conducted right ventricular sense (RVs) event, or, in the event that a ventricular pace occurs upon the expiration of the extended AV interval between said A-event and the ventricular pace; and

means for programming one of a relatively short AV interval and a minimum AV interval as the test AV interval.

22. An apparatus according to claim 21, further comprising:

means for delivering a left ventricle-only pacing stimulus (LVp) and in the event that no right ventricular sense (RVs) event occurs prior to delivery of a next-scheduled right ventricular pace (RVp) declaring loss of capture (LOC) of said LV chamber.

23. An apparatus according to claim 21, further comprising:

delivering a left ventricle-only pacing stimulus (LVp) and in the event that an RVs event occurs more than 40ms prior to the measured PR interval declaring capture of said LV.

24. An apparatus according to claim 23, further comprising:

means for confirming the initial declaration of LV LOC in the event that LOC is again declared.

25. An apparatus according to claim 24, further comprising:

means for issuing an output signal reflecting the LV LOC declaration.

26. An apparatus according to claim 25, wherein said output signal is stored within a memory structure.

27. An apparatus according to claim 25, wherein said output signal is provided wirelessly to one of a cardiac device programming apparatus and a remote work station.

28. An apparatus according to claim 27, wherein said remote work station comprises one of a patient monitor, a clinician transceiver, a processor-controlled device coupled to a patient information network.

29. An apparatus according to claim 28, wherein said patient monitor comprises means for alerting said patient to the results of at least one of the parameters of said ventricular capture verification method.

30. An apparatus according to claim 29, wherein the at least one of the parameters comprises: a test AV interval, a PR interval, a set of temporal pacing parameters, a pacing stimulation metric; a heart rate, an activity rate, a metabolic state, a presence of an ischemia episode, a presence of pulmonary edema.

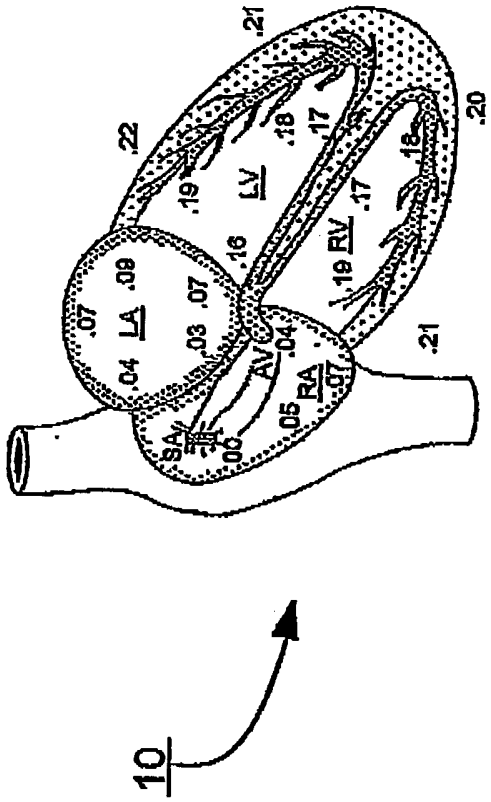


FIG. 1

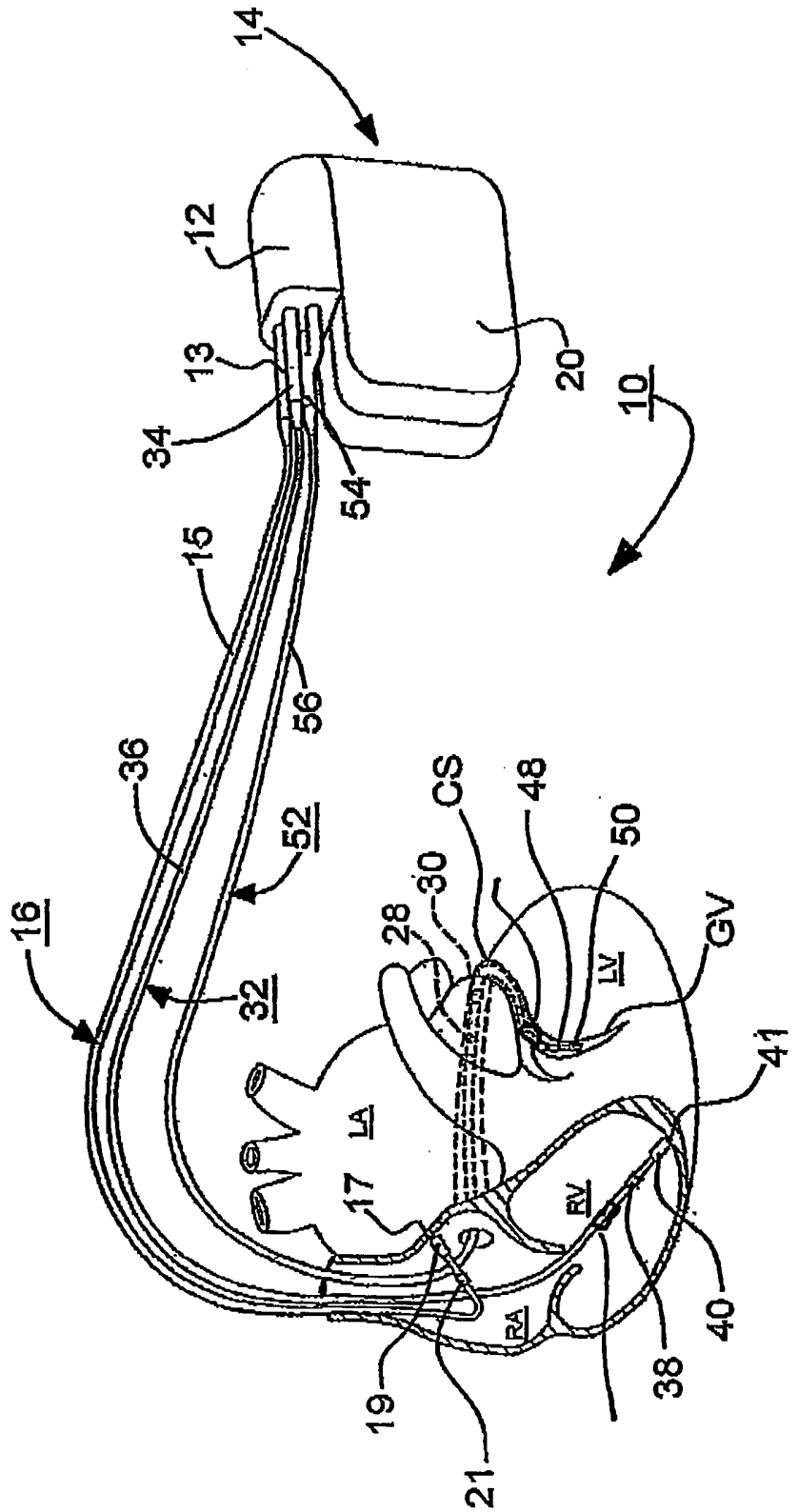

14
12
13
34
54
20
10
15
56
36
52
16
32
CS
48
50
30
28
LV
GV
41
LA
17
RV
RA
19
21
38
40

FIG. 2

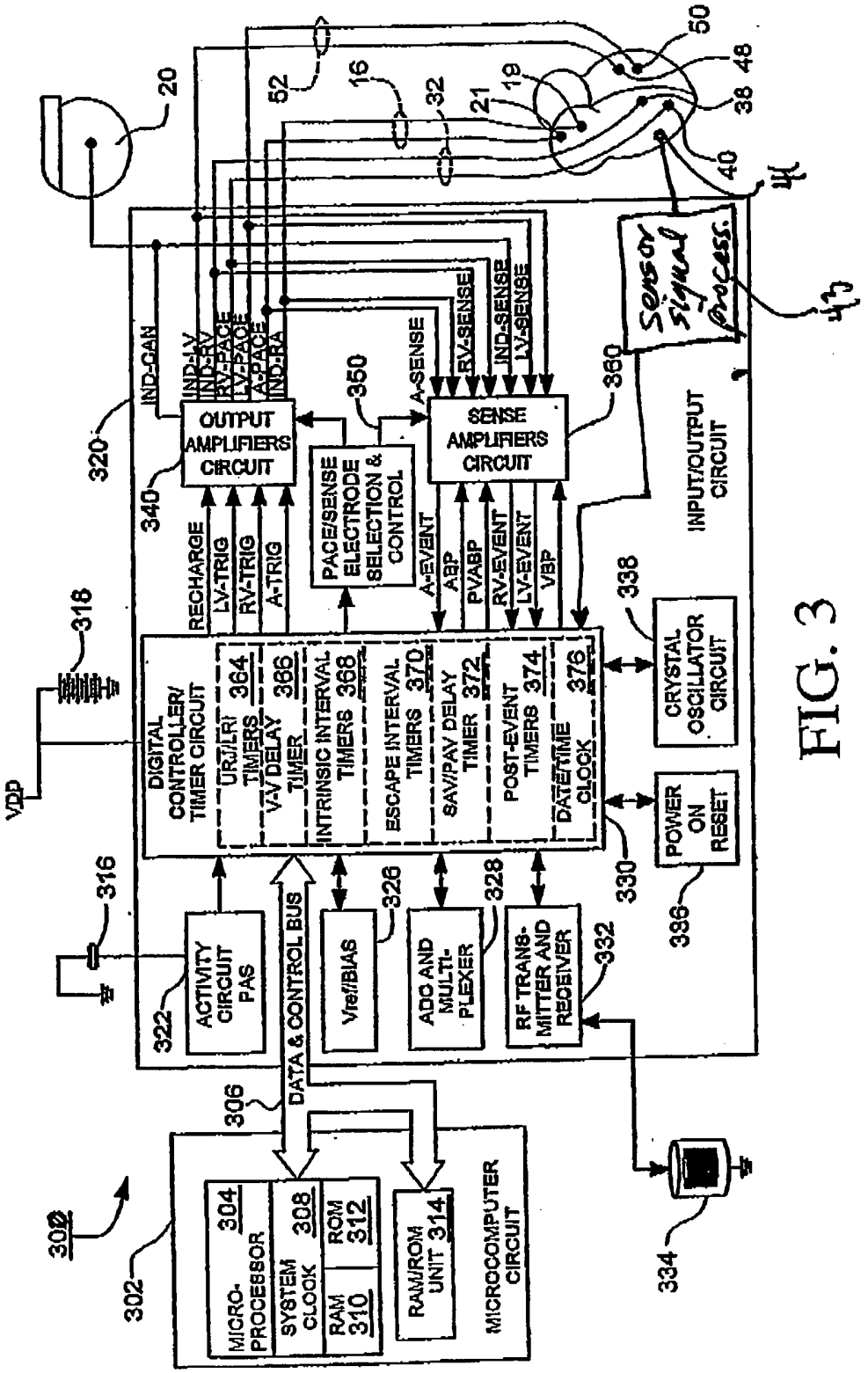

20
52
16
32
21
19
50
48
38
40
44
Sensor Signal Process.
43
IND-CAN
IND-LV
IND-RV
RV-PACE
LV-PACE
A-PACE
IND-RA
A-SENSE
RV-SENSE
IND-SENSE
LV-SENSE
320
340
350
360
OUTPUT AMPLIFIERS CIRCUIT
PACE/SENSE ELECTRODE SELECTION & CONTROL
SENSE AMPLIFIERS CIRCUIT
INPUT/OUTPUT CIRCUIT
RECHARGE
LV-TRIG
RV-TRIG
A-TRIG
A-EVENT
ABP
PVABP
RV-EVENT
LV-EVENT
VBP
318
VDD
338
DIGITAL CONTROLLER/ TIMER CIRCUIT
URI/LRI TIMERS 364
V-V DELAY TIMER 366
INTRINSIC INTERVAL TIMERS 368
ESCAPE INTERVAL TIMERS 370
SAV/PAV DELAY TIMER 372
POST-EVENT TIMERS 374
DATE/TIME CLOCK 376
CRYSTAL OSCILLATOR CIRCUIT
POWER ON RESET
330
336
316
322
ACTIVITY CIRCUIT PAS
DATA & CONTROL BUS
326
Vref/BIAS
328
ADC AND MULTI-PLEXER
332
RF TRANS-MITTER AND RECEIVER
306
302
MICRO-PROCESSOR 304
SYSTEM CLOCK 308
ROM 312
RAM 310
RAM/ROM UNIT 314
MICROCOMPUTER CIRCUIT
334

FIG. 3

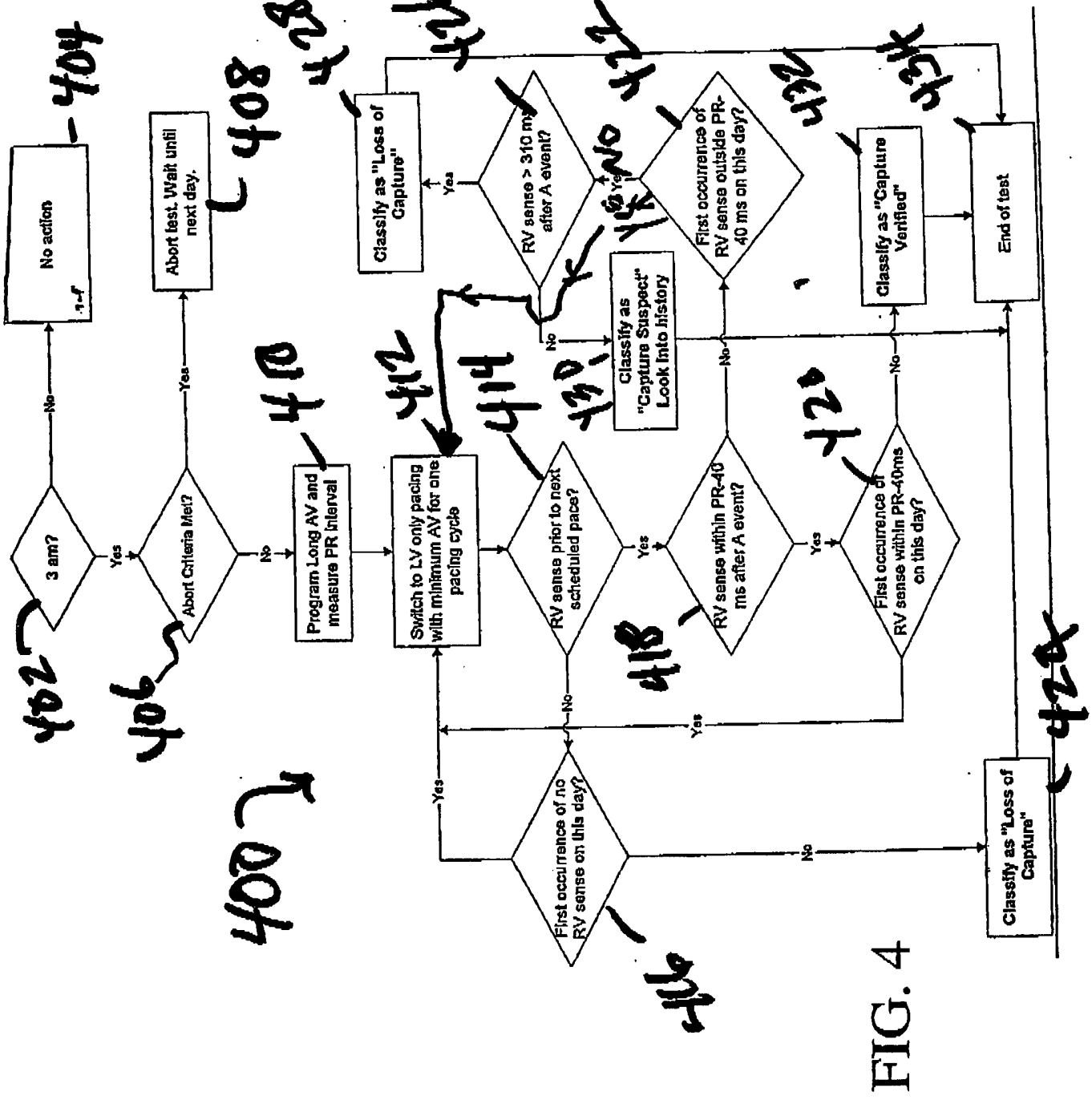

No action
Abort test. Wait until next day.
Classify as "Loss of Capture"
RV sense > 310 ms after A event?
First occurrence of RV sense outside PR-40 ms on this day?
Classify as "Capture Verified"
End of test
3 am?
Abort Criteria Met?
Program Long AV and measure PR interval
Switch to LV only pacing with minimum AV for one pacing cycle
RV sense prior to next scheduled pace?
Classify as "Capture Suspect" Look into history
RV sense within PR-40 ms after A event?
First occurrence of RV sense within PR-40ms on this day?
First occurrence of no RV sense on this day?
Classify as "Loss of Capture"
No
Yes
402
404
406
408
410
412
414
416
418
420
422
424
426
428
430
432
434
400

FIG. 4

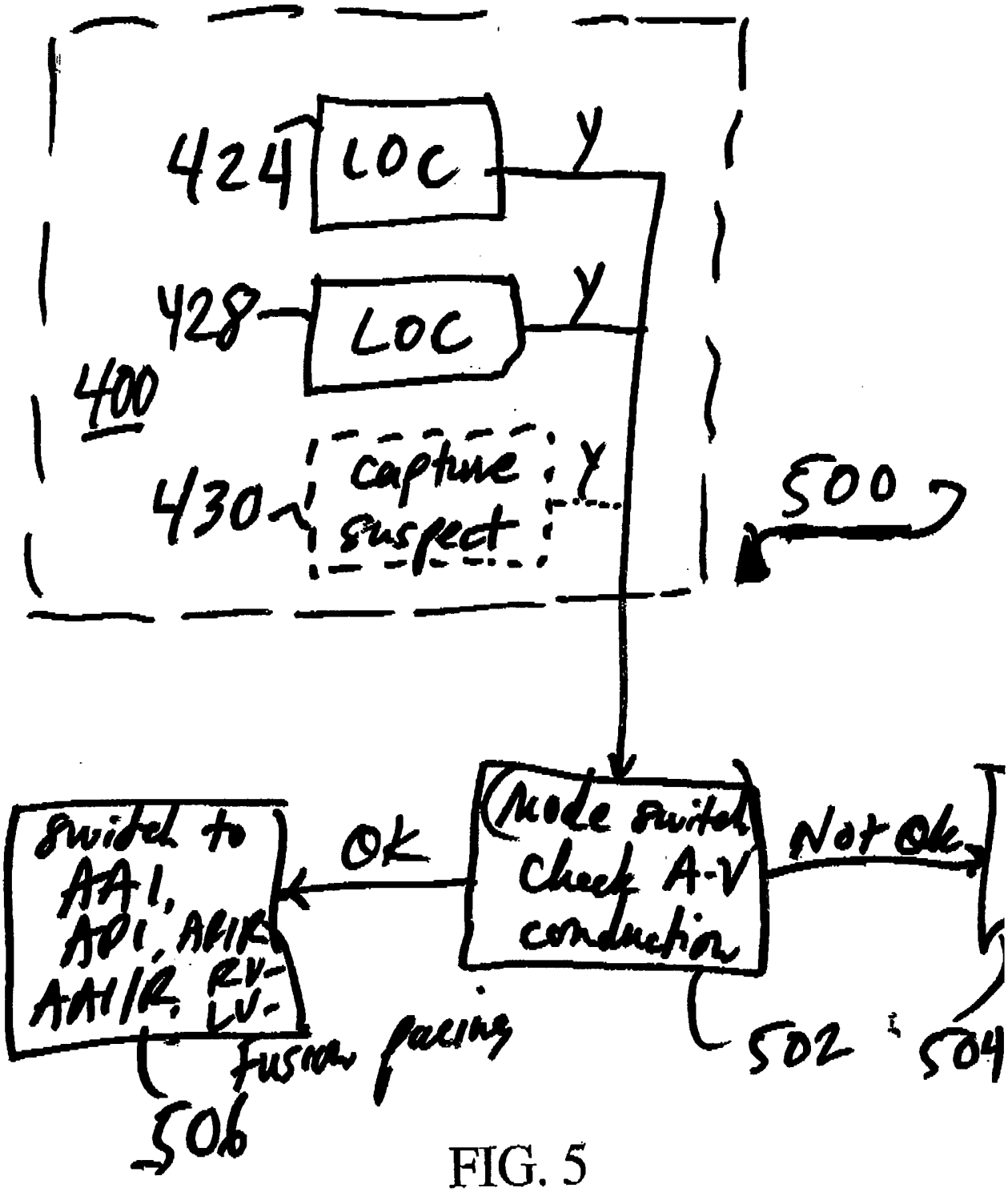

424
LOC
Y
428
LOC
Y
400
430
capture suspect
Y
500
Switch to AAI, ADI, AAIR, AAI/R, RV-LV-Fusion pacing
OK
Mode Switch Check A-V conduction
Not Ok
506
502
504

FIG. 5

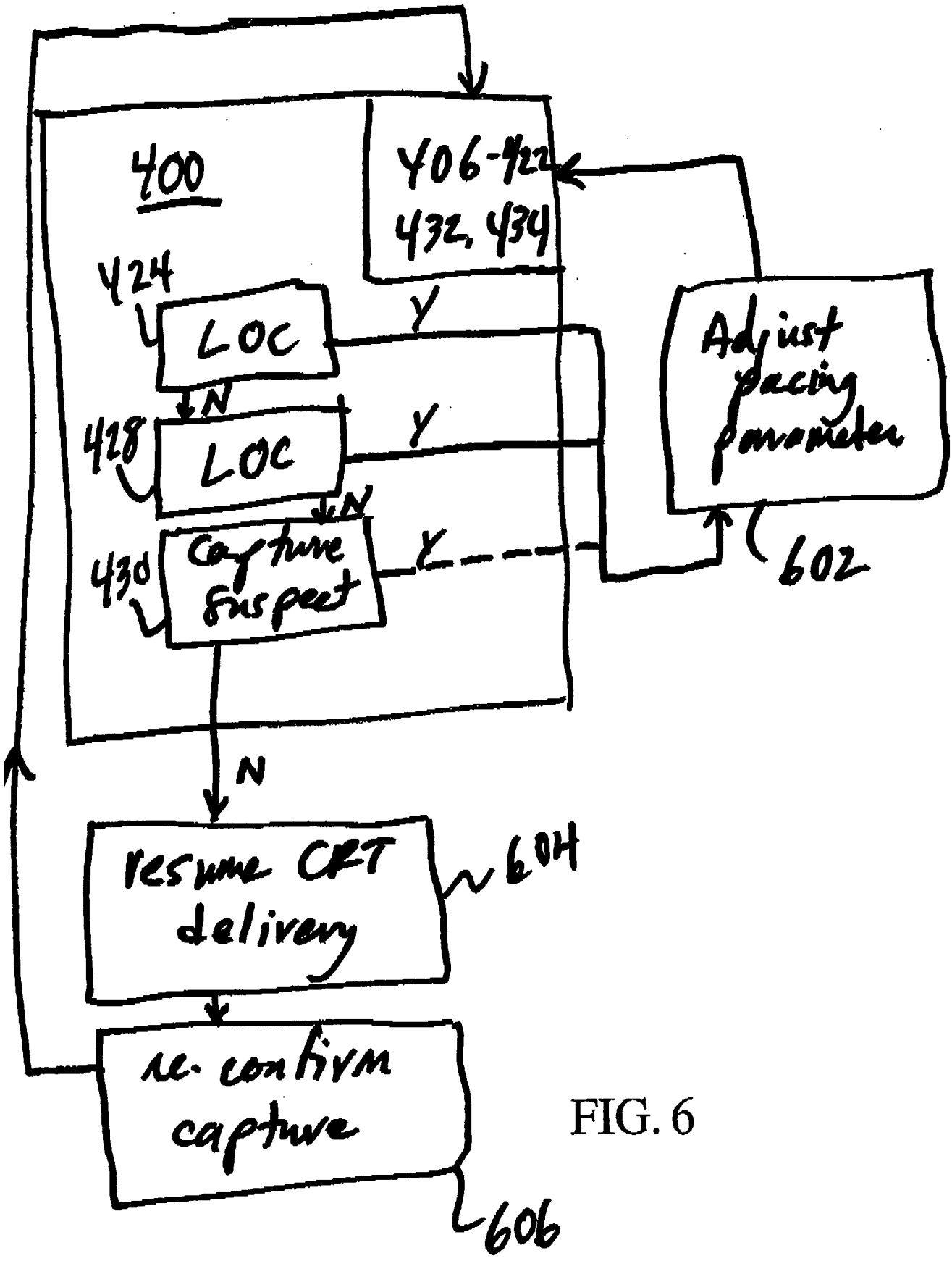

400
406-422
432, 434
424
LOC
Y
N
428
LOC
Y
N
430
Capture Suspect
Y
N
Adjust pacing parameter
602
N
Resume CRT delivery
604
re-confirm capture
606

FIG. 6

INTERNATIONAL SEARCH REPORT

Inter nal application No
PCT/US2005/046055

A. CLASSIFICATION OF SUBJECT MATTER
A61N1/37

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61N

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2003/195579 A1 (BRADLEY KERRY ET AL) 16 October 2003 (2003-10-16) paragraphs [0021] - [0024], [0051], [0091], [0108]	1-30
A	US 2003/153957 A1 (BRADLEY KERRY) 14 August 2003 (2003-08-14) the whole document	1-30
A	US 2003/083709 A1 (ZHU QINGSHENG ET AL) 1 May 2003 (2003-05-01) the whole document	1-30

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 March 2006	05/04/2006

Name and mailing address of the ISA/	Authorized officer
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1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter nal application No
PCT/US2005/046055

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2003195579 A1	16-10-2003	NONE	
US 2003153957 A1	14-08-2003	NONE	
US 2003083709 A1	01-05-2003	US 2005240237 A1	27-10-2005