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(54) METHODS AND SYSTEMS FOR MAPPING CARDIAC REPOLARIZATION

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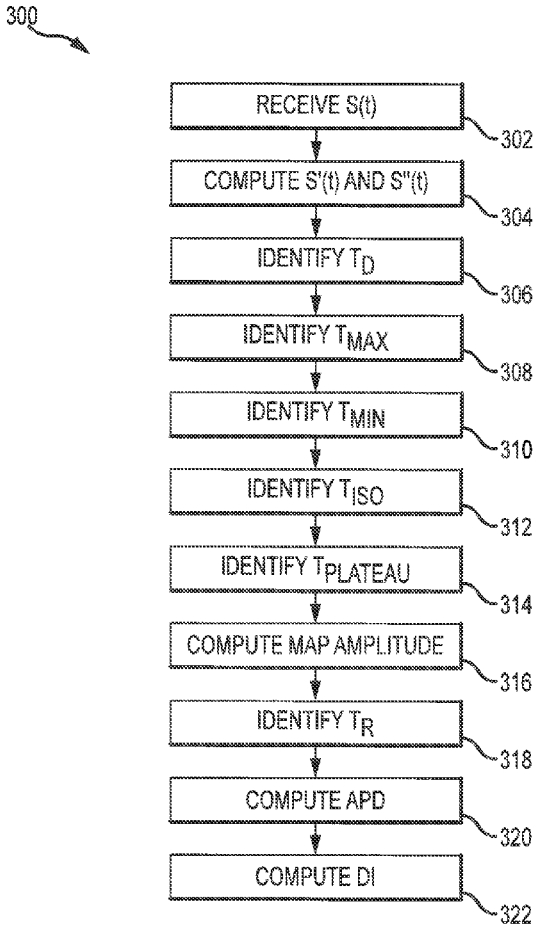
(57) **ABSTRACT**

Cardiac repolarization activity can be mapped using action potential duration ("APD") and/or activation recovery interval ("ARI"). APD can be measured using a bipolar electrogram signal measured, for example, using a monophasic action potential ("MAP") catheter. ARI can be measured using unipolar electrogram signals. The electrogram signal is used to identify a depolarization tick time. A repolarization tick time can be identified using either a point in time when the electrogram signal passes below a threshold or via local maxima and minima of a first derivative of the electrogram signal. Diastolic intervals can also be computed using depolarization and repolarization tick times.



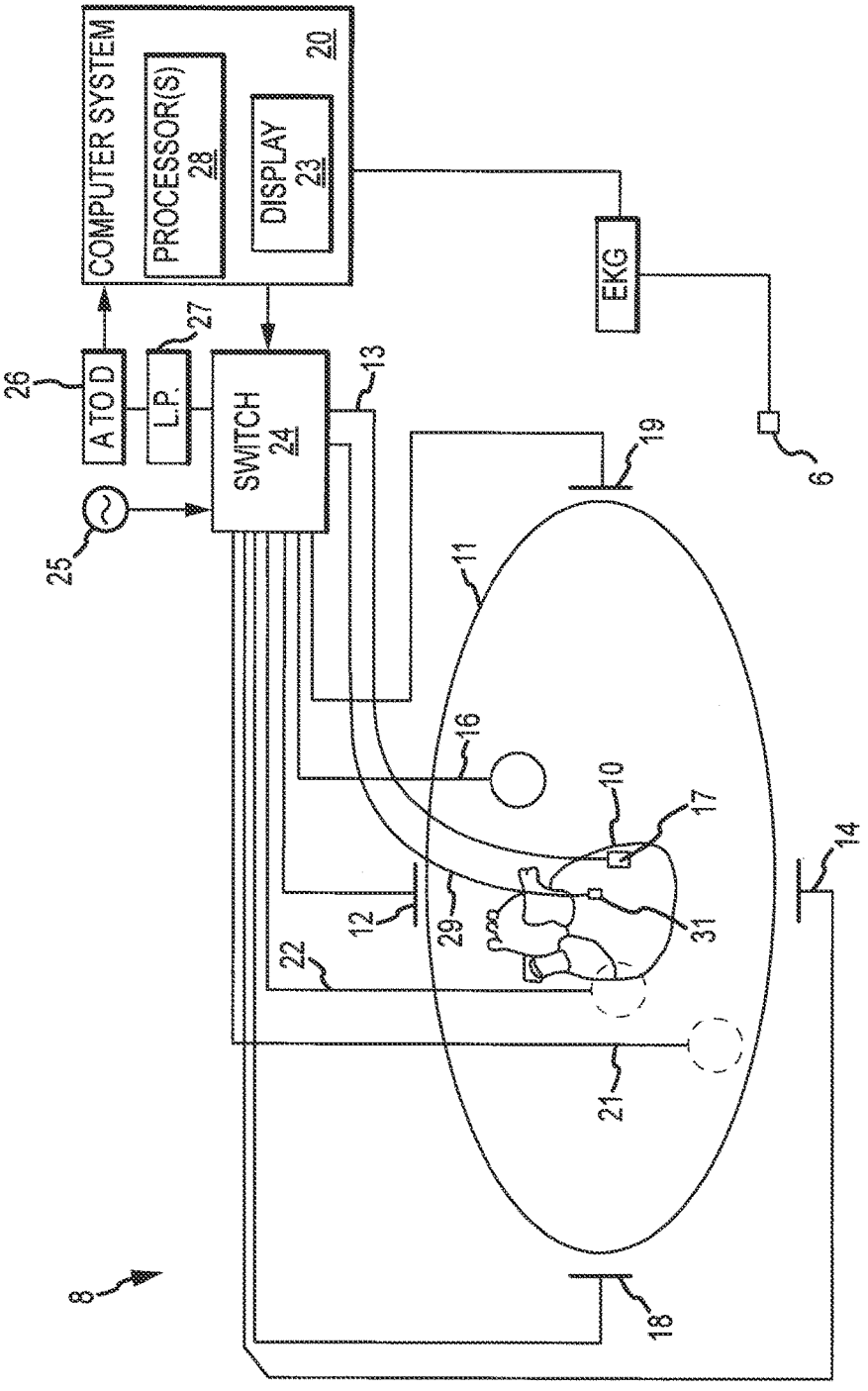

COMPUTER SYSTEM
20
PROCESSOR(S)
28
DISPLAY
23
EKG
A TO D
L.P.
27
26
SWITCH
24
13
25
19
6
11
16
10
17
14
12
29
31
22
21
18
8

FIG.1

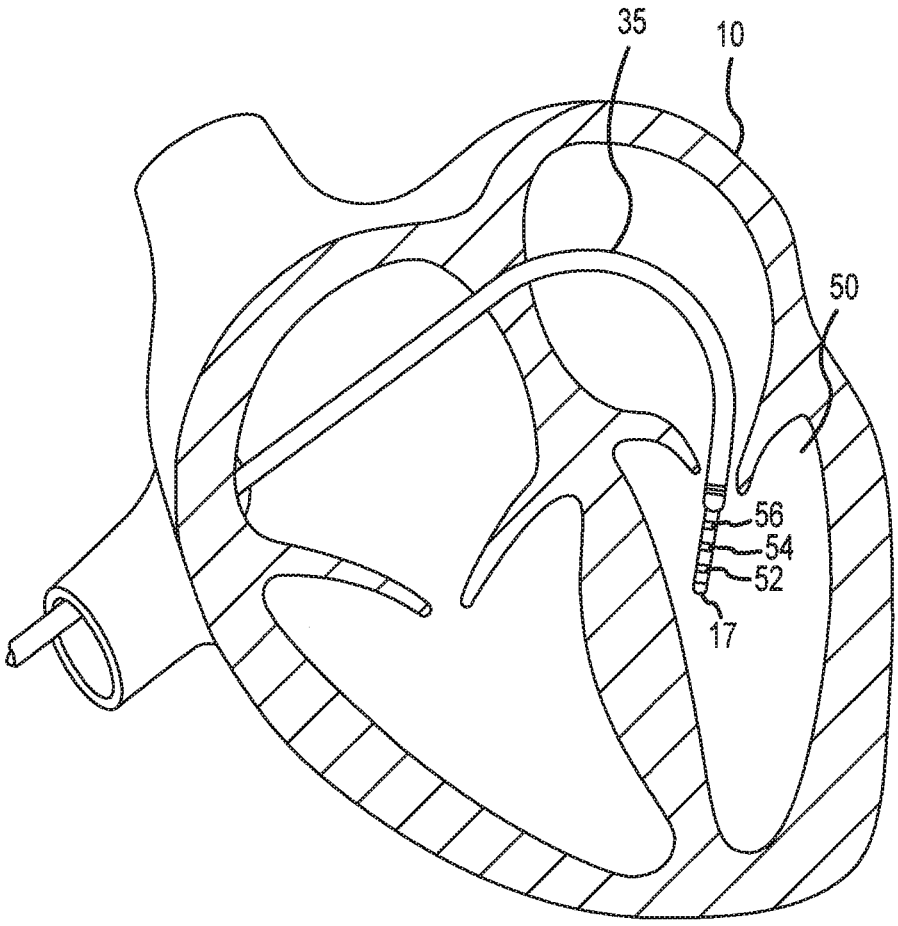


FIG.2

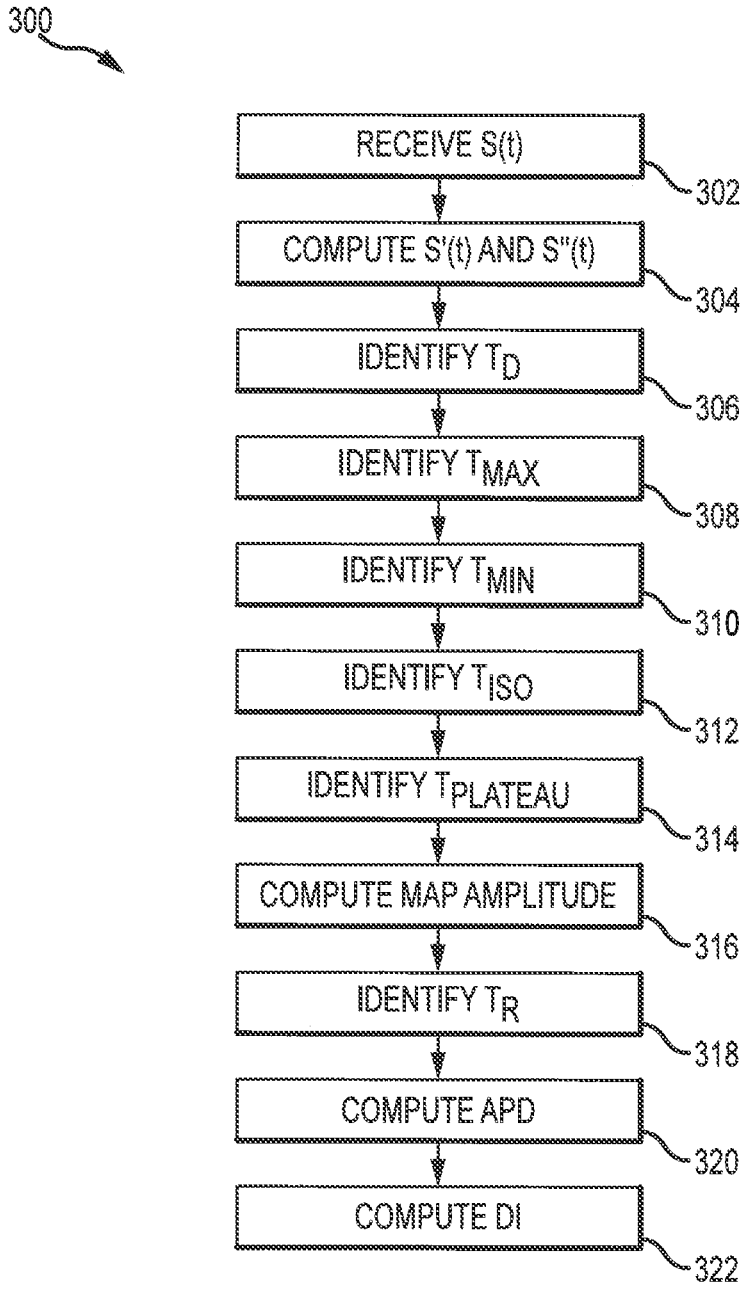

300
RECEIVE S(t)
302
COMPUTE S'(t) AND S"(t)
304
IDENTIFY T_D
306
IDENTIFY T_{MAX}
308
IDENTIFY T_{MIN}
310
IDENTIFY T_{ISO}
312
IDENTIFY $T_{PLATEAU}$
314
COMPUTE MAP AMPLITUDE
316
IDENTIFY T_R
318
COMPUTE APD
320
COMPUTE DI
322

FIG.3

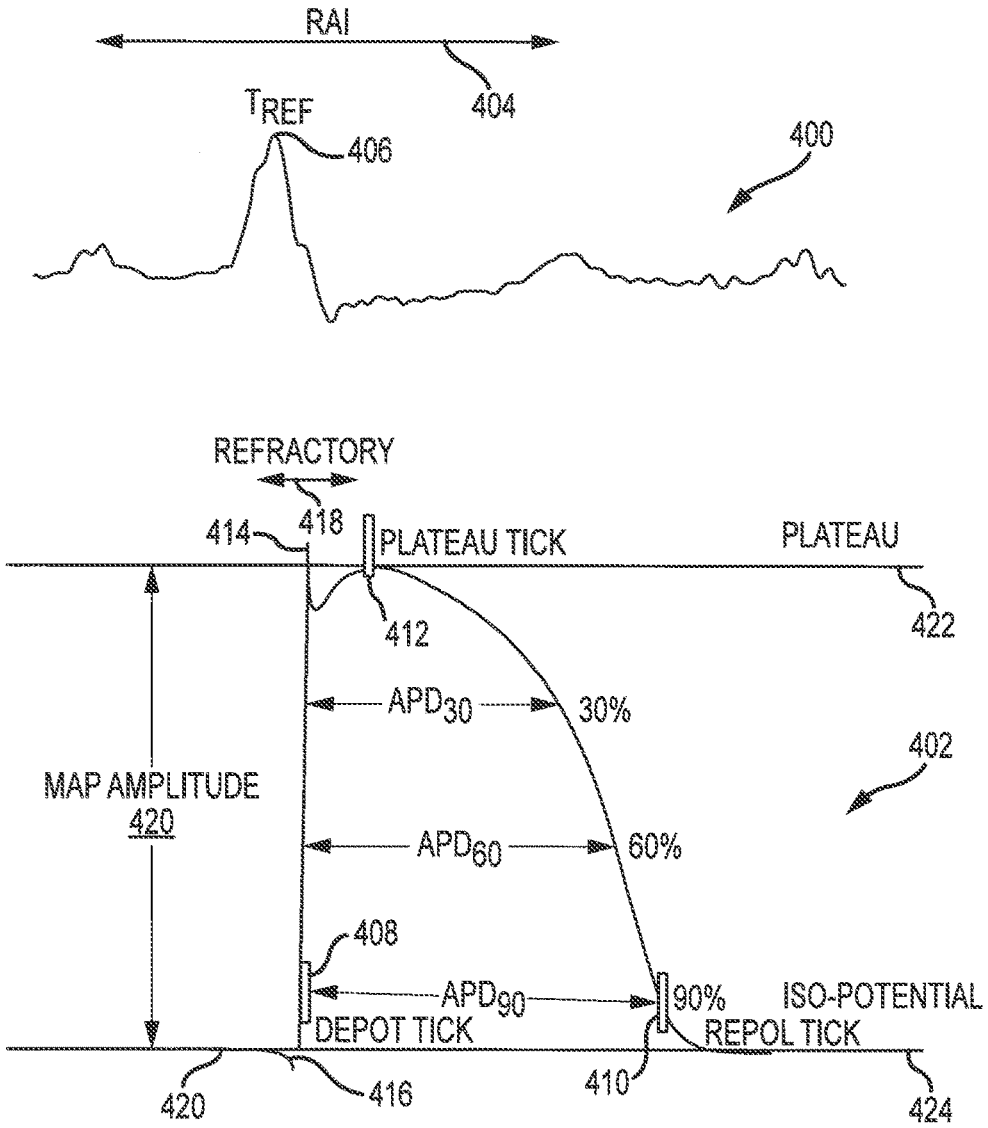

RAI
404
T_{REF}
406
400
REFRACTORY
414
418
PLATEAU TICK
PLATEAU
412
422
APD_{30}
30%
402
MAP AMPLITUDE
420
APD_{60}
60%
408
APD_{90}
90%
ISO-POTENTIAL
DEPOT TICK
REPOL TICK
420
416
410
424

FIG.4

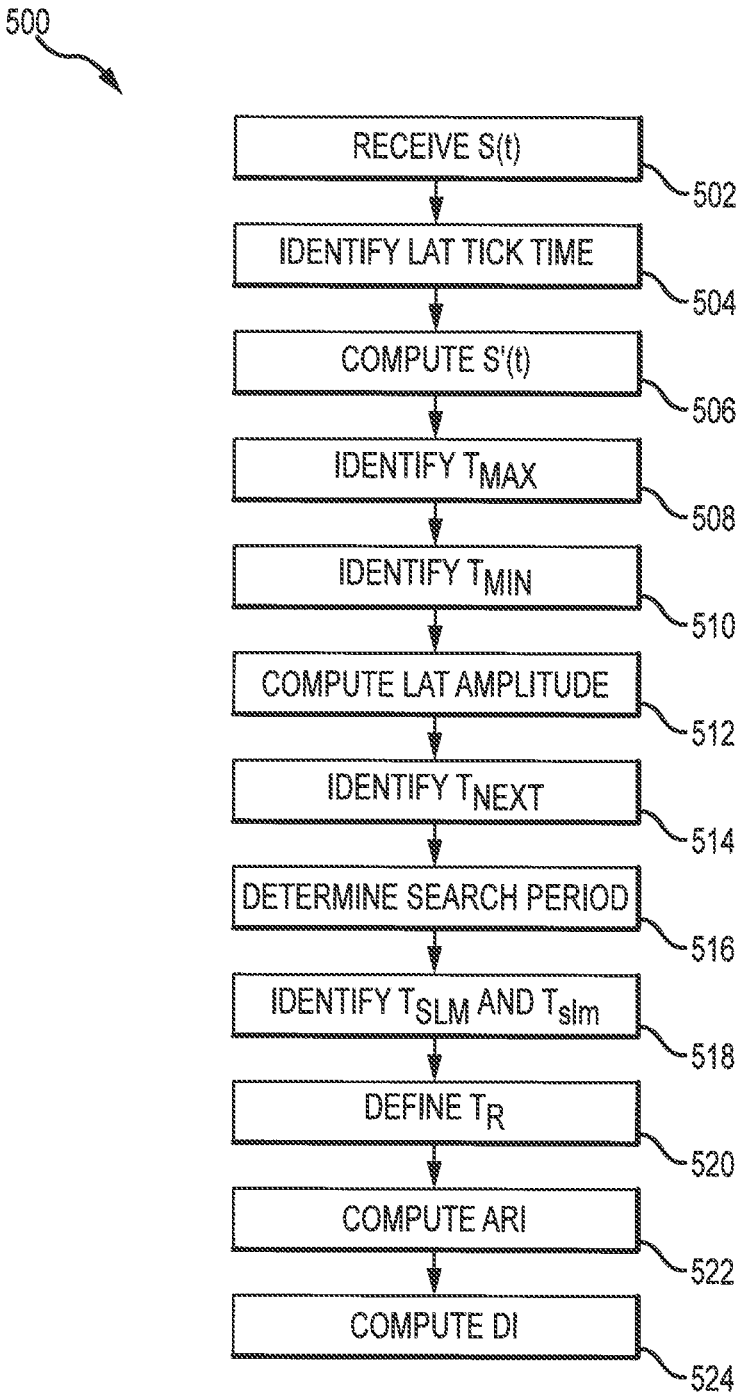

500
RECEIVE S(t)
502
IDENTIFY LAT TICK TIME
504
COMPUTE S'(t)
506
IDENTIFY T_{MAX}
508
IDENTIFY T_{MIN}
510
COMPUTE LAT AMPLITUDE
512
IDENTIFY T_{NEXT}
514
DETERMINE SEARCH PERIOD
516
IDENTIFY T_{SLM} AND T_{slm}
518
DEFINE T_R
520
COMPUTE ARI
522
COMPUTE DI
524

FIG.5

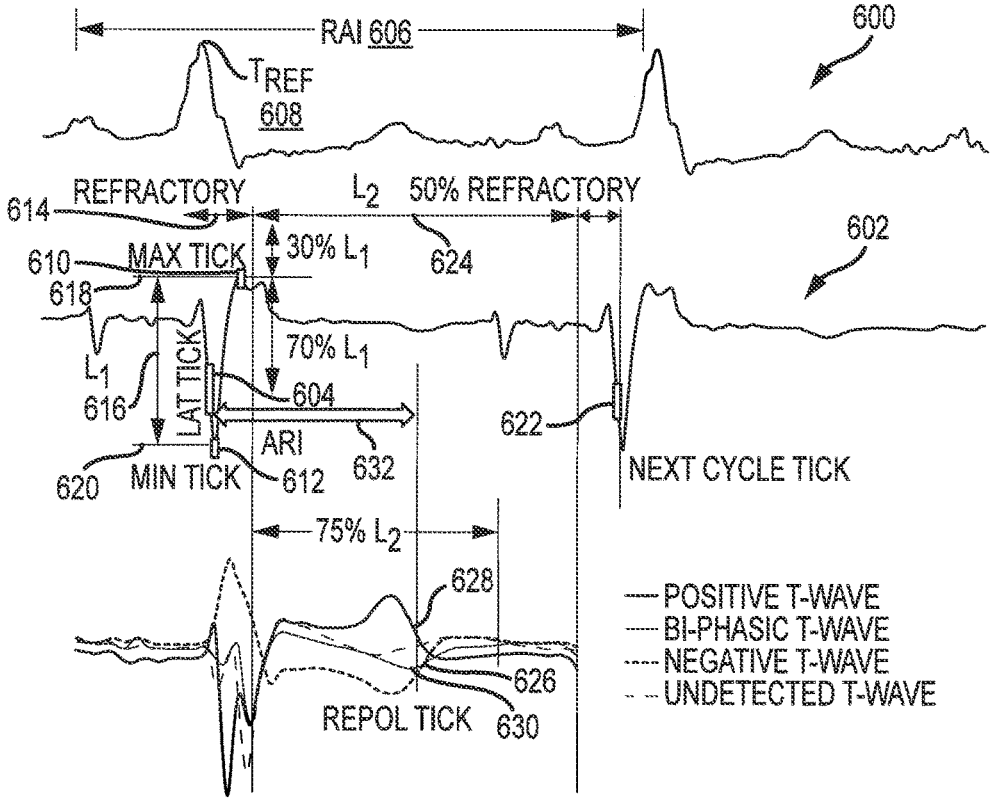

RAI 606
600
T_{REF} 608
614
REFRACTORY
L_2
50% REFRACTORY
602
610
MAX TICK
30% L_1
624
618
70% L_1
L_1
616
LAT TICK
604
622
ARI
632
620
MIN TICK
612
NEXT CYCLE TICK
75% L_2
628
626
REPOL TICK
630
POSITIVE T-WAVE
BI-PHASIC T-WAVE
NEGATIVE T-WAVE
UNDETECTED T-WAVE

FIG.6

METHODS AND SYSTEMS FOR MAPPING CARDIAC REPOLARIZATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional application No. 62/238,323, filed 7 Oct. 2015, which is hereby incorporated by reference as though fully set forth herein.

BACKGROUND

[0002] The instant disclosure relates to electrophysiological mapping, such as may be performed in cardiac diagnostic and therapeutic procedures. In particular, the instant disclosure relates to systems, apparatuses, and methods for mapping cardiac repolarization activity, including action potential duration ("APD") and activation recovery interval ("ARI").

[0003] It is known to map cardiac depolarization activity, for example as part of an electrophysiology study. Cardiac repolarization activity, however, is not generally mapped during electrophysiology studies. One reason for this disparity is that depolarization wave potentials are typically stronger than repolarization wave potentials, increasing the complexity of mapping the repolarization activity.

[0004] Nonetheless, it can be desirable to map repolarization activity. For example, research suggests that repolarization plays a role in arrhythmogenesis, such that maps of repolarization activity might be of use in identifying better substrate for ablation therapy.

BRIEF SUMMARY

[0005] Disclosed herein is a method of mapping cardiac repolarization activity, including the following steps: receiving an electrogam signal S(t) at a signal processor; and using the signal processor: computing a second derivative S"(t) of the electrogram signal S(t) for a preset window about a reference time T_{ref}; identifying a depolarization tick time T_D within the preset window using S"(t); identifying a repolarization tick time T_R using S(t), wherein the repolarization tick time T_R is identified as a point in time when S(t) passes below a preset threshold; and computing an action potential duration for the preset window using the depolarization tick time T_D and the repolarization tick time T_R. It is contemplated that the electrogram signal S(t) can be a bipolar electrogram signal from a monophasic action potential ("MAP") catheter. It is also contemplated that the reference time T_{ref} can be detected using a reference cardiac signal.

[0006] In embodiments, the step of computing a second derivative S"(t) of the electrogram S(t) for a preset window about a reference time T_{ref} includes computing a first derivative S'(t) of the electrogram S(t) for the preset window about the reference time T_{ref} according to a formula

$$S'(t) = \frac{S(t+\Delta t) - S(t)}{\Delta t},$$

wherein Δt comprises a preset time interval, such as about 3 ms.

[0007] According to aspects of the disclosure, the step of identifying a depolarization tick time T_D within the preset window using S"(t) can include: identifying a time point within the preset window when S"(t) reaches its maximum; and designating the time point when S"(t) reaches its maximum as the depolarization tick time T_D.

[0008] The preset threshold can be computed as a function of an amplitude of S(t), such as 10% of the amplitude of S(t). In other embodiments, the preset threshold can be computed according to the following steps: identifying a maximum tick time T_{max} and a minimum tick time T_{min} within a preset refractory window surrounding the depolarization tick time T_D using S(t); identifying an isopotential tick time T_{iso} occurring before T_{min} using S"(t); identifying a plateau tick time $T_{plateau}$ occurring after T_{max} using a first derivative S'(t) of S(t); defining the amplitude A of S(t) as $S(T_{plateau})-S(T_{iso})$; and defining the preset threshold as $S(T_{plateau})-x*A$, $0<x<1$.

[0009] The method optionally also includes computing a diastolic interval for the preset window using the depolarization tick time T_D within the preset window and an immediately previous repolarization tick time T_{R-1}.

[0010] In another embodiment of the disclosure, a method of mapping cardiac repolarization activity includes: receiving an electrogram signal S(t) at a signal processor; and using the signal processor: identifying a local activation time ("LAT") tick time within a preset window about a reference time T_{ref}; defining the LAT tick time as a depolarization tick time T_D for the preset window; computing a first derivative S'(t) of the electrogram signal S(t) for the preset window; identifying a repolarization tick time T_R using local maxima and local minima of S'(t); and computing an activation recovery interval for the preset window using the depolarization tick time T_D and the repolarization tick time T_R. The electrogram signal S(t) can include a unipolar electrogram signal. In addition, the step of identifying a local activation time ("LAT") tick time within a preset window about a reference time T_{ref} can include identifying the LAT tick time within the preset window about the reference time T_{ref} using a bipolar electrogram signal.

[0011] In embodiments, the step of computing a first derivative S'(t) of the electrogram signal S(t) for the preset window includes computing the first derivative S'(t) according to a formula

$$S'(t) = \frac{S(t+\Delta t) - S(t)}{\Delta t},$$

wherein Δt comprises a preset time interval, such as about 3 ms.

[0012] According to aspects of the disclosure, the step of identifying a repolarization tick time T_R using local maxima and local minima of S'(t) includes: identifying a maximum tick time T_{max} and a minimum tick time T_{min} within a preset refractory window ΔRW surrounding the depolarization tick time T_D using S(t); computing a LAT amplitude L_1 using $S(T_{max})$ and $S(T_{min})$; identifying a next cycle tick T_{next} occurring after T_{max} using S(t); determining a search period following the depolarization tick time T_D for the repolarization tick time T_R; identifying a time T_{SLM} during the search period at which S'(t) reaches a local maximum; identifying a time T_{slm} during the search period at which S'(t) reaches a local minimum; and defining the repolarization tick time T_R using one or more of T_{SLM} and T_{slm}.

[0013] Further, it is contemplated that the step of identifying a next cycle tick T_{next} occurring after T_{max} using S(t)

can include: defining a local minimum threshold higher than $S(T_{min})$; defining a local maximum threshold higher than $S(T_{max})$; analyzing S(t) after T_{max}; and identifying T_{next} as a first to occur of: a time at which S(t) drops below the local minimum threshold; a time at which S(t) exceeds the local maximum threshold; and a time at which S(t) ends. The local minimum threshold can be computed as $S(T_{min})+0.3*L_1$; and the local maximum threshold can be computed as $S(T_{max})+0.3*L_1$.

[0014] According to aspects of the disclosure, the step of determining a search period following the depolarization tick time T_D for the repolarization tick time T_R includes: computing a search interval L_2 as $T_{next}-T_D-2(\Delta RW)$; defining a start of the search period at $T_D+\Delta RW$; and defining an end of the search period at $T_D+\Delta RW+0.75*L_2$.

[0015] According to additional aspects of the disclosure, the step of defining the repolarization tick time T_R using one or more of T_{SLM} and T_{slm} includes: defining T_R as

$$\min(T_{SLM}, T_{sim}) + \frac{T_{SLM} + T_{sim}}{2}$$

for a biphasic T-wave; defining T_R as T_{SLM} for a negative T-wave; and defining T_R as T_{slm} for a positive T-wave.

[0016] The method optionally includes computing a diastolic interval for the preset window using the depolarization tick time T_D for the preset window and an immediately previous repolarization tick time T_{R-1}.

[0017] Also disclosed herein is a system for mapping cardiac repolarization activity. The system includes: a cardiac repolarization detection processor configured: to receive an electrogram S(t); to identify a depolarization tick time T_D using the electrogram S(t); to identify a repolarization tick time T_R using either a point in time when S(t) passes below a preset threshold or local maxima and local minima of a first derivative S'(t) of the electrogram S(t); and to compute a cardiac repolarization time period using the depolarization tick time T_D and the repolarization tick time T_R. The cardiac repolarization detection processor can also be configured to compute a diastolic interval using the depolarization tick time T_D and a an immediately previous repolarization tick time T_{R-1}. The repolarization time period can he an action potential duration and/or an activation recovery interval.

[0018] The foregoing and other aspects, features, details, utilities, and advantages of the present invention will be apparent from reading the following description and claims, and from reviewing the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] FIG. **1** is a schematic of an electrophysiology system, such as may be used in an electrophysiology study including mapping cardiac repolarization activity.

[0020] FIG. **2** depicts an exemplary multi-electrode catheter used in an electrophysiology study.

[0021] FIG. **3** is a flowchart of representative steps that can he followed to map cardiac repolarization activity using a monophasic action potential ("MAP") catheter to determine action potential duration ("APD").

[0022] FIG. **4** is a representation of cardiac electrical activity with various tick times and other values referenced in the flowchart of FIG. **3** annotated thereon.

[0023] FIG. **5** is a flowchart of representative steps that can be followed to map cardiac repolarization activity using unipolar electrograms ("EGMs") to determine activation recovery interval ("ARI").

[0024] FIG. **6** is a representation of cardiac electrical activity with various tick times and other values referenced in the flowchart of FIG. **5** annotated thereon.

DETAILED DESCRIPTION

[0025] The present disclosure provides methods, apparatuses, and systems for the creation of electrophysiology maps (e.g., electrocardiographic maps) that provide information regarding cardiac repolarization activity. Certain embodiments of the disclosure will he explained with reference to the use of bipolar electrograms, such as measured by a MAP catheter, to determine APD. Other embodiments of the disclosure will be explained with reference to the use of unipolar electrograms to determine ARI. It should be understood, however, that the teachings herein can be applied to good advantage in other contexts, such as mapping local electrogram QRS activity width, which can be representative of the pattern of wave conduction.

[0026] FIG. **1** shows a schematic diagram of an electrophysiology system **8** for conducting cardiac electrophysiology studies by navigating a cardiac catheter and measuring electrical activity occurring in a heart **10** of a patient **11** and three-dimensionally mapping the electrical activity and/or information related to or representative of the electrical activity so measured. System **8** can be used, for example, to create an anatomical model of the patient's heart **10** using one or more electrodes. System **8** can also he used to measure electrophysiology data, including, but not limited to, electrical activation data (e.g., local activation time ("LAT")), at a plurality of points along a cardiac surface and store the measured data in association with location information for each measurement point at which the electrophysiology data was measured, for example to create an electrophysiology map of the patient's heart **10** (or a portion thereof).

[0027] As one of ordinary skill in the art will recognize, and as will be further described below, system **8** can determine the location, and in some aspects the orientation, of objects, typically within a three-dimensional space, and express those locations as position information determined relative to at least one reference.

[0028] For simplicity of illustration, the patient **11** is depicted schematically as an oval. In the embodiment shown in FIG. **1**, three sets of surface electrodes (e.g., patch electrodes) are shown applied to a surface of the patient **11**, defining three generally orthogonal axes, referred to herein as an x-axis, a y-axis, and a z-axis. In other embodiments the electrodes could be positioned in other arrangements, for example multiple electrodes on a particular body surface. As a further alternative, the electrodes do not need to be on the body surface, but could be positioned internally to the body or on an external frame.

[0029] In FIG. **1**, the x-axis surface electrodes **12**, **14** are applied to the patient along a first axis, such as on the lateral sides of the thorax region of the patient (e.g., applied to the patient's skin underneath each arm) and may be referred to as the Left and Right electrodes. The y-axis electrodes **18**, **19** are applied to the patient along a second axis generally orthogonal to the x-axis, such as along the inner thigh and neck regions of the patient, and may be referred to as the

Left Leg and Neck electrodes. The z-axis electrodes **16**, **22** are applied along a third axis generally orthogonal to both the x-axis and the y-axis, such as along the sternum and spine of the patient in the thorax region, and may be referred to as the Chest and Back electrodes. The heart **10** lies between these pairs of surface electrodes **12**/**14**, **18**/**19**, and **16**/**22**.

[0030] An additional surface reference electrode (e.g., a "belly patch") **21** provides a reference and/or ground electrode for the system **8**. The belly patch electrode **21** may be an alternative to a fixed intra-cardiac electrode **31**, described in further detail below. It should also be appreciated that, in addition, the patient **11** may have most or all of the conventional electrocardiogram ("ECG" or "EKG") system leads in place. In certain embodiments, for example, a standard set of 12 ECG leads may be utilized for sensing electrocardiograms on the patient's heart **10**. This ECG information is available to the system **8** (e.g., it can be provided as input to computer system **20**). Insofar as ECG leads are well understood, and for the sake of clarity in the figures, only one lead **6** and its connection to computer system **20** is illustrated in FIG. **1**.

[0031] A representative catheter **13** having at least one electrode **17** (e.g., a distal electrode) is also depicted in schematic fashion in FIG. **1**. This representative catheter electrode **17** can be referred to as a "measurement electrode" or a "roving electrode." Typically, multiple electrodes on catheter **13**, or on multiple such catheters, will be used. In one embodiment, for example, system **8** may utilize sixty-four electrodes on twelve catheters disposed within the heart and/or vasculature of the patient.

[0032] In other embodiments, system **8** may utilize a single catheter that includes multiple (e.g., eight) splines, each of which in turn includes multiple (e.g., eight) electrodes. Of course, these embodiments are merely exemplary, and any number of electrodes and catheters may be used. Indeed, in some embodiments, a high density mapping catheter, such as the EnSite™ Array™ non-contact mapping catheter of St. Jude Medical, Inc., can be utilized.

[0033] Likewise, it should be understood that catheter **13** (or multiple such catheters) are typically introduced into the heart and/or vasculature of the patient via one or more introducers and using familiar procedures. For purposes of this disclosure, a segment of an exemplary multi-electrode catheter **13** is shown in FIG. **2**. In FIG. **2**, catheter **13** extends into the left ventricle **50** of the patient's heart **10** through a transseptal sheath **35**. The use of a transseptal approach to the left ventricle is well known and will be familiar to those of ordinary skill in the art, and need not be further described herein. Of course, catheter **13** can also be introduced into the heart **10** in any other suitable manner.

[0034] Catheter **13** includes electrode **17** on its distal tip, as well as a plurality of additional measurement electrodes **52**, **54**, **56** spaced along its length in the illustrated embodiment. Typically, the spacing between adjacent electrodes will be known, though it should be understood that the electrodes may not be evenly spaced along catheter **13** or of equal size to each other. Since each of these electrodes **17**, **52**, **54**, **56** lies within the patient, location data may be collected simultaneously for each of the electrodes by system **8**.

[0035] Similarly, each of electrodes **17**, **52**, **54**, and **56** can be used to gather electrophysiological data from the cardiac surface. For example, in some embodiments, catheter **13** is capable of sensing MAPs (e.g., from bipolar electrograms). The ordinarily skilled artisan will be familiar with various modalities for the acquisition and processing of electrophysiology data points (including, for example, both contact and non-contact electrophysiological mapping and the collection of both unipolar and bipolar electrograms), such that further discussion thereof is not necessary to the understanding of the cardiac repolarization activity mapping techniques disclosed herein. Likewise, various techniques familiar in the art can be used to generate a graphical representation from the plurality of electrophysiology data points. Insofar as the ordinarily skilled artisan will appreciate how to create electrophysiology maps from electrophysiology data points, the aspects thereof will only be described herein to the extent necessary to understand the maps disclosed herein.

[0036] Returning now to FIG. **1**, in some embodiments, a fixed reference electrode **31** (e.g., attached to a wall of the heart **10**) is shown on a second catheter **29**. For calibration purposes, this electrode **31** may be stationary (e.g., attached to or near the wall of the heart) or disposed in a fixed spatial relationship with the roving electrodes (e.g., electrodes **17**, **52**, **54**, **56**), and thus may be referred to as a "navigational reference" or "local reference," The fixed reference electrode **31** may be used in addition or alternatively to the surface reference electrode **21** described above. In many instances, a coronary sinus electrode or other fixed electrode in the heart **10** can be used as a reference for measuring voltages and displacements; that is, as described below, fixed reference electrode **31** may define the origin of a coordinate system.

[0037] Each surface electrode is coupled to a multiplex switch **24**, and the pairs of surface electrodes are selected by software running on a computer **20**, which couples the surface electrodes to a signal generator **25**. Alternately, switch **24** may be eliminated and multiple (e.g., three) instances of signal generator **25** may be provided, one for each measurement axis (that is, each surface electrode pairing).

[0038] The computer **20**, for example, may comprise a conventional general-purpose computer, a special-purpose computer, a distributed computer, or any other type of computer. The computer **20** may comprise one or more processors **28**, such as a single central processing unit (CPU), or a plurality of processing units, commonly referred to as a parallel processing environment, which may execute instructions to practice the various aspects disclosed herein.

[0039] Generally, three nominally orthogonal electric fields are generated by a series of driven and sensed electric dipoles (e.g., surface electrode pairs **12**/**14**, **18**/**19**, and **16**/**22**) in order to realize catheter navigation in a biological conductor. Alternatively, these orthogonal fields can be decomposed and any pairs of surface electrodes can be driven as dipoles to provide effective electrode triangulation. Likewise, the electrodes **12**, **14**, **18**, **19**, **16**, and **22** (or any other number of electrodes) could be positioned in any other effective arrangement for driving a current to or sensing a current from an electrode in the heart. For example, multiple electrodes could be placed on the back, sides, and/or belly of patient **11**. For any desired axis, the potentials measured across the roving electrodes resulting from a predetermined set of drive (source-sink) configurations may be combined algebraically to yield the same effective potential as would be obtained by simply driving a uniform current along the orthogonal axes.

[0040] Thus, any two of the surface electrodes **12**, **14**, **16**, **18**, **19**, **22** may be selected as a dipole source and drain with respect to a ground reference, such as belly patch **21**, while the unexcited electrodes measure voltage with respect to the ground reference. The roving electrodes **17**, **52**, **54**, **56** placed in the heart **10** are exposed to the field from a current pulse and are measured with respect to ground, such as belly patch **21**. In practice the catheters within the heart **10** may contain more or fewer electrodes than the four shown, and each electrode potential may be measured. As previously noted, at least one electrode may be fixed to the interior surface of the heart to form a fixed reference electrode **31**, which is also measured with respect to ground, such as belly patch **21**, and which may be defined as the origin of the coordinate system relative to which localization system **8** measures positions. Data sets from each of the surface electrodes, the internal electrodes, and the virtual electrodes may all be used to determine the location of the roving electrodes **17**, **52**, **54**, **56** within heart **10**.

[0041] The measured voltages may be used by system **8** to determine the location in three-dimensional space of the electrodes inside the heart, such as roving electrodes **17**, **52**, **54**, **56**, relative to a reference location, such as reference electrode **31**. That is, the voltages measured at reference electrode **31** may be used to define the origin of a coordinate system, while the voltages measured at roving electrodes **17**, **52**, **54**, **56** may be used to express the location of roving electrodes **17**, **52**, **54**, **56** relative to the origin. In some embodiments, the coordinate system is a three-dimensional (x, y, z) Cartesian coordinate system, although other coordinate systems, such as polar, spherical, and cylindrical coordinate systems, are contemplated.

[0042] As should be clear from the foregoing discussion, the data used to determine the location of the electrode(s) within the heart is measured while the surface electrode pairs impress an electric field on the heart. The electrode data may also be used to create a respiration compensation value used to improve the raw location data for the electrode locations as described in U.S. Pat. No. 7,263,397, which is hereby incorporated herein by reference in its entirety. The electrode data may also be used to compensate for changes in the impedance of the body of the patient as described, for example, in U.S. Pat. No. 7,885,707, which is also incorporated herein by reference in its entirety.

[0043] In one representative embodiment, the system **8** first selects a set of surface electrodes and then drives them with current pulses. While the current pulses are being delivered, electrical activity, such as the voltages measured with at least one of the remaining surface electrodes and in vivo electrodes, is measured and stored. Compensation for artifacts, such as respiration and/or impedance shifting, may be performed as indicated above.

[0044] In some embodiments, system **8** is the EnSite™ Velocity™ cardiac mapping and visualization system of St. Jude Medical, Inc., which generates electrical fields as described above, or another such system that relies upon electrical fields. Other systems, however, may be used in connection with the present teachings, including for example, the CARTO navigation and location system of Biosense Webster, Inc., the AURORA® system of Northern Digital Inc., or Sterotaxis' NIOBE® Magnetic Navigation System, all of Which utilize magnetic fields rather than electrical fields. The localization and mapping systems described in the following patents (all of which are hereby incorporated by reference in their entireties) can also be used with the present invention: U.S. Pat. Nos. 6,990,370; 6,978,168; 6,947,785; 6,939,309; 6,728,562; 6,640,119; 5,983,126; and 5,697,377.

[0045] One basic methodology of mapping cardiac repolarization activity will be explained with reference to the flowchart **300** of representative steps presented as FIG. **3**. In some embodiments, for example, flowchart **300** may represent several exemplary steps that can be carried out by the computer **20** of FIG. **1** (e.g., by one or more processors **28**) to generate a map of cardiac repolarization activity as described herein. It should be understood that the representative steps described below can be either hardware- or software-implemented. For the sake of explanation, the term "signal processor" is used herein to describe both hardware- and software-based implementations of the teachings herein.

[0046] More particularly, flowchart **300** in FIG. **3** illustrates a series of representative steps that may be carried out to map cardiac repolarization activity using APD. In step **302**, an electrogram signal, denoted S(t) (and illustrated as lower trace **402** in FIG. **4**), is received at a signal processor (e.g., by one or more processors **28** within computer **20**). For mapping APD, it is desirable that the electrogram signal **402** be a bipolar electrogram signal, such as from a MAP catheter (see, e.g., U.S. Pat. No. 5,398,683, which is hereby incorporated by reference as though fully set forth herein).

[0047] In block **304**, the first and second derivatives of S(t), denoted S'(t) and S"(t), respectively, are computed. In embodiments, the first derivative Sit) is calculated using the formula

$$S'(t) = \frac{S(t+\Delta t) - S(t)}{\Delta t},$$

where Δt is a preset time interval, such as 3 ms. Similarly, the second derivative S"(t) can be computed according to the formula

$$S''(t) = \frac{S'(t+\Delta t) - S'(t)}{\Delta t}.$$

[0048] More specifically, S'(t) and S"(t) are computed for a preset window, referred to herein as a "Roving Activation Interval" ("RAI") **404**, about a reference time point **406**. denoted T_{ref}, in block **304**. According to aspects disclosed herein, T_{ref} **406** is set to correspond to QRS activity detected using a user-defined reference cardiac signal, such as the signal from an EKG lead or the signal from an in vivo reference electrode. The upper trace **400** in FIG. **4** is a representative reference cardiac signal, such as may be used to determine T_{ref} **406**.

[0049] Likewise, the width of RAI **404** can be user-defined. According to aspects of the disclosure, RAI **404** is between about 100 ms and about 300 ms wide.

[0050] In block **306**, a depolarization tick time **408**, denoted T_D, is identified within the RAI using S"(t). For example, T_D **408** can be designated as the time point within RAI **404** where S"(t) reaches its maximum.

[0051] The next several steps illustrated in FIG. **3** are directed at identifying a repolarization tick time **410**, denoted T_R, for the current cardiac trigger (that is, the

current beat). It should be understood that the repolarization tick time **410** for the current cardiac trigger need not occur within RAI **404**. Rather, according to some aspects of the disclosure, the repolarization tick time **410** can be identified within a user-defined minimum cycle length threshold ("CL_{min}") of $T_{plateau}$ **412** (described further below). In any event, however, T_R **410** is typically identified as a point in time where S(t) **402** passes below a preset threshold, as further described below.

[0052] In blocks **308** and **310** respectively, a maximum tick time **414** (denoted T_{max}) and a minimum tick time **416** (denoted T_{min}) are identified within a preset refractory window **418** (denoted ΔRW) of T_D **408**. T_{max} **414** is the time point, within the refractory window **418**, at which S(t) **402** achieves its local maximum; conversely, T_{min} **416** is the time point, within the refractory window **418**, at which S(t) **402** achieves its local minimum.

[0053] In embodiments, the preset refractory window **418** is **12** ms to either side of the depolarization tick time **408** (i.e., T_D±12 ms). The teachings herein are not limited, however, to this specific refractory window, and other refractory windows, including refractory windows that are not centered on the depolarization tick time **408**, can be employed without departing from the scope of the teachings herein.

[0054] An isopotential tick time **420**, denoted T_{iso}, is detected in block **312**. According to aspects of the disclosure, the isopotential tick time **420** is detected as a time point before the minimum tick time **416** at which the absolute value of S"(t) drops below a preset threshold, such as 0.01. If no such point exists, then flowchart **300** can terminate for the current beat.

[0055] Similarly, in block **314**, a plateau tick time **412** ($T_{plateau}$) is detected. According to aspects of the disclosure, the plateau tick time **412** is detected as a time point after the maximum tick time **414** at which the absolute value of S'(t) goes below a preset threshold, such as 0.5. If no such point exists, then flowchart **300** can terminate for the current beat.

[0056] In block **316**, a MAP amplitude **420** (represented by the letter A in this disclosure and shown as "MAP amplitude" in FIG. **4**) is computed as the difference between $S(T_{plateau})$ **422** and $S(T_{iso})$ **424**. The MAP amplitude **420** is used to determine the preset threshold that will be used to determine the repolarization tick time **410** (block **318**), for example by setting the preset threshold as a fraction of the MAP amplitude **420**. In embodiments disclosed herein, the preset threshold is set at 10% of the MAP amplitude **420** (that is, the repolarization tick time is detected when S(t) drops below $S(T_{plateau})$–0.9(A)). If no such point exists within the minimum cycle length threshold of the plateau tick time **412** (that is, if the amplitude of S(t) **402** does not diminish sufficiently within a preset time of when it plateaus), then flowchart **300** can terminate for the current beat.

[0057] Once the repolarization tick time **410** is detected, APD can be computed as the difference between the depolarization and repolarization tick times **408**, **410** respectively (block **320**). In addition, a diastolic interval can be computed as the difference between the depolarization tick time and an immediately previous repolarization tick time (i.e., T_{R-1}).

[0058] Another basic methodology of mapping cardiac repolarization activity will be explained with reference to the flowchart **500** of representative steps presented as FIG. **5**. That is, flowchart **500** may represent several exemplary steps that can be carried out by the computer **20** of FIG. **1** (e.g. by one or more processors **28**) to generate a map of cardiac repolarization activity as described herein. Once again, it should be understood that the representative steps described below can be either hardware- or software-implemented, and the term "signal processor" will again be used to describe both hardware- and software-based implementations of the teachings herein.

[0059] More particularly, flowchart **500** in FIG. **5** illustrates a series of representative steps that may be carried out to map cardiac repolarization activity using ARI. In step **502**, an electrogram signal, again denoted S(t) and illustrated as lower trace **602** in FIG. **6**, is received at a signal processor (e.g., by one or more processors **28** within computer **20**). For mapping ARI, it is desirable that the electrogram signal be a unipolar electrogram signal.

[0060] In block **504**, a local activation time ("LAT") tick time **604** is identified within a preset window, again referred to as a "Roving Activation Interval" ("RAI") **606**, about a reference time point T_{ref} **608**. Similar to trace **400** in FIG. **4**, the upper trace **600** in FIG. **6** is a representative reference cardiac signal, such as may be used to identify T_{ref} **608**. In embodiments of the disclosure, the LAT tick time **604** is identified using a bipolar electrogram signal **602**. Once identified, the LAT tick time **604** is defined as the depolarization tick time T_D for the RAI **606**.

[0061] In block **506**, the first derivative S'(t) of SW **602** is computed. As described in connection with FIG. **3**, S'(t) can be computed as

$$S'(t) = \frac{S(t+\Delta t) - S(t)}{\Delta t},$$

where Δt is a preset time interval, such as 3 ms.

[0062] The next several steps illustrated in FIG. **5** are directed at identifying a repolarization tick time T_R for the current cardiac trigger (that is, the current beat). It should be understood that the repolarization tick time for the current cardiac trigger need not occur within the RAI **606**. Rather, as described below, a search period following the depolarization tick time **604** is defined, and the repolarization tick time is detected within this search period. In any event, however, T_R is typically identified using local maxima and local minima of S'(t), as described in further detail below.

[0063] In blocks **508** and **510** respectively, a maximum tick time **610** (denoted T_{max}) and a minimum tick time **612** (denoted T_{min}) are identified within a preset refractory window **614** (denoted ΔRW) of T_D **604**. T_{max} **610** is the time point, within the refractory window **614**, at Which S(t) **602** achieves its local maximum; conversely. $T_{min\ 612}$ is the time point, within the refractory window **614**, at which S(t) **602** achieves its local minimum.

[0064] In embodiments, the preset refractory window **614** is 50 ms to either side of the depolarization tick time **604** (i.e., T_D±50 ms). The teachings herein are not limited, however, to this specific refractory window, and other refractory windows, including refractory windows that are not centered on the depolarization tick time **604**, can be employed without departing from the spirit of the teachings herein. A LAT amplitude **616** (L_i) is computed as the difference between $S(T_{max})$ **618** and $S(T_{min})$ **620** in block **512**.

[0065] A next cycle tick time T_{next} **622** is identified in block **514**. It is contemplated that T_{next} **622** can be identified with reference to a local minimum threshold, which is higher than $S(T_{min})$ **620**, and a local maximum threshold, which is higher than $S(T_{max})$ **618**.

[0066] The LAT amplitude **616** can be used to compute the local minimum and local maximum thresholds. For example, the local minimum threshold can Be computed as $S(T_{min})+0.3*L_1$, and the local maximum threshold can be computed as $S(T_{max})+0.3*L_1$.

[0067] In aspects of the disclosure, T_{next} **622** is designated as the time point at which the first of the following occurs after T_{max} **610**: (1) S(t) **602** drops below the local minimum threshold; (2) S(t) **602** exceeds the local maximum threshold; or (3) S(t) **602** ends.

[0068] A search period, following the depolarization tick time **604**, for the repolarization tick time is determined in block **516**. In certain embodiments, the search period begins at $T_D+\Delta RW$ and ends at $TD+\Delta RW+0.75(L_2)$, where L_2 (**624**) is a search interval defined as $T_{next}-T_D-2(\Delta RW)$.

[0069] In block **518**, two additional tick times are identified: T_{SLM} and T_{slm}. T_{SLM} is the time point during the search period at which S'(t) reaches a local maximum, while T_{slm} is the time point during the search period at which S'(t) reaches a local minimum.

[0070] In block **520**, the repolarization tick time is defined using one or more of T_{SLM} and T_{slm}. According to aspects of the instant disclosure, the definition of the repolarization tick time depends on whether the T-wave is biphasic, negative, or positive. Thus, for example, the repolarization tick time can be defined as T_{SLM} **626** for a negative T-wave and as T_{slm} **628** for a positive T-wave. For a biphasic T-wave, the repolarization tick time **630** can be defined using the formula

$$\min(T_{SLM}, T_{sim}) + \frac{T_{SLM} + T_{sim}}{2}.$$

[0071] Once the repolarization tick time is defined, ART **632** can be computed (block **522**) as the difference between the depolarization and repolarization tick times. In addition, a diastolic interval can be computed (block **524**) as the difference between the depolarization tick time and an immediately previous repolarization tick time T_{R-1}).

[0072] Although several embodiments of this invention have been described above with a certain degree of particularity, those skilled in the art could make numerous alterations to the disclosed embodiments without departing from the spirit or scope of this invention.

[0073] All directional references (e.g., upper, lower, upward, downward, left, right, leftward, rightward, top, bottom, above, below, vertical, horizontal, clockwise, and counterclockwise) are only used for identification purposes to aid the reader's understanding of the present invention, and do not create limitations, particularly as to the position, orientation, or use of the invention. Joinder references (e.g., attached, coupled, connected, and the like) are to be construed broadly and may include intermediate members between a connection of elements and relative movement between elements. As such, joinder references do not necessarily infer that two elements are directly connected and in fixed relation to each other.

[0074] It is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative only and not limiting. Changes in detail or structure may be made without departing from the spirit of the invention as defined in the appended claims.

What is claimed is:

1. A method of mapping cardiac repolarization activity, comprising:

receiving an electrogram signal S(t) at a signal processor; and

using the signal processor:

computing a second derivative S"(t) of the electrogram signal S(t) for a preset window about a reference time T_{ref};

identifying a depolarization tick time T_D within the preset window using S"(t);

identifying a repolarization tick time T_R using S(t), wherein the repolarization tick time T_R is identified as a point in time when S(t) passes below a preset threshold; and

computing an action potential duration for the preset window using the depolarization tick time T_D and the repolarization tick time T_R.

2. The method according to claim **1**, wherein receiving an electrogram signal S(t) at a signal processor comprises receiving a bipolar electrogram signal SW from a monophasic action potential ("MAP") catheter at the signal processor.

3. The method according to claim **1**, further comprising detecting the reference time T_{ref} using a reference cardiac signal.

4. The method according to claim **1**, wherein computing a second derivative S"(t) of the electrogram S(t) for a preset window about a reference time T_{ref} further comprises computing a first derivative S'(t) of the electrogram S(t) for the preset window about the reference time T_{ref} according to a formula

$$S'(t) = \frac{S(t+\Delta t) - S(t)}{\Delta t},$$

wherein Δt comprises a preset time interval.

5. The method according to claim **1**, wherein identifying a depolarization tick time T_D within the preset window using S"(t) comprises:

identifying a time point within the preset window when S"(t) reaches its maximum; and

designating the time point when S"(t) reaches its maximum as the depolarization tick time T_D.

6. The method according to claim wherein the preset threshold is computed as a function of an amplitude of S(t).

7. The method according to claim **6**, wherein the preset threshold is computed according to steps comprising:

identifying a maximum tick time T_{max} and a minimum tick time T_{min} within a preset refractory window surrounding the depolarization tick time T_D using S(t);

identifying an isopotential tick time T_{iso} occurring before T_{min} using S"(t);

identifying a plateau tick time $T_{plateau}$ occurring after T_{max} using a first derivative S'(t) of S(t);

defining the amplitude A of S(t) as $S(T_{plateau})-S(T_{iso})$; and

defining the preset threshold as $S(T_{plateau})-x*A$, $0<x<1$.

8. The method according to claim **1**, further comprising computing a diastolic interval for the preset window using

the depolarization tick time T_D within the preset window and an immediately previous repolarization tick time T_{R-1}.

9. A method of mapping cardiac repolarization activity, comprising:

receiving an electrogram signal S(t) at a signal processor; and

using the signal processor:

identifying a local activation time ("LAT") tick time within a preset window about a reference time T_{ref};

defining the LAT tick time as a depolarization tick time T_D for the preset window;

computing a first derivative S'(t) of the electrogram signal S(t) for the preset window;

identifying a repolarization tick time T_R using local maxima and local minima of S'(t); and

computing an activation recovery interval for the preset window using the depolarization tick time T_D and the repolarization tick time T_R.

10. The method according to claim **9**, wherein the electrogram signal S(t) comprises a unipolar electrogram signal.

11. The method according to claim **9**, wherein identifying a local activation time ("LAT") tick time within a preset window about a reference time T_{ref} comprises identifying the LAT tick time within the preset window about the reference time T_{ref} using a bipolar electrogram signal.

12. The method according to claim **9**, wherein computing a first derivative S'(t) of the electrogram signal S(t) for the preset window comprises computing the first derivative S'(t) according to a formula

$$S'(t) = \frac{S(t+\Delta t) - S(t)}{\Delta t},$$

wherein Δt comprises a preset time interval.

13. The method according to claim **10**, wherein identifying a repolarization tick time T_R using local maxima and local minima of S'(t) comprises:

identifying a maximum tick time T_{max} and a minimum tick time T_{min} within a preset refractory window ΔRW surrounding the depolarization tick time T_D using S(t);

computing a LAT amplitude L_1 using $S(T_{max})$ and $S(T_{min})$;

identifying a next cycle tick T_{next} occurring after T_{max} using S(t);

determining a search period following the depolarization tick time T_D for the repolarization tick time T_R;

identifying a time T_{SLM} during the search period at which S'(t) reaches a local maximum;

identifying a time T_{slm} during the search period at which S'(t) reaches a local minimum; and

defining the repolarization tick time T_R using one or more of T_{SLM} and T_{slm}.

14. The method according to claim **13**, wherein identifying a next cycle tick T_{next} occurring after T_{max} using S(t) comprises:

defining a local minimum threshold higher than $S(T_{min})$;

defining a local maximum threshold higher than $S(T_{max})$;

analyzing S(t) after T_{max}; and

identifying T_{next} as a first to occur of:

a time at which S(t) drops below the local minimum threshold;

a time at which S(t) exceeds the local maximum threshold; and

a time at which S(t) ends.

15. The method according to claim **14**, wherein:

the local minimum threshold is computed as $S(T_{min})+0.3*L_1$; and

the local maximum threshold is computed as $S(T_{max})+0.3*L_1$.

16. The method according to claim **13**, wherein determining a search period following the depolarization tick time T_D for the repolarization tick time T_R comprises:

computing a search interval L_2 as $T_{next}-T_D-2(\Delta RW)$;

defining a start of the search period at $T_D+\Delta RW$; and

defining an end of the search period at $T_D+\Delta RW+0.75*L_2$.

17. The method according to claim **13**, wherein defining the repolarization tick time T_R using one or more of T_{SLM} and T_{slm} comprises:

defining T_R as

$$\min(T_{SLM}, T_{sim}) + \frac{T_{SLM} + T_{sim}}{2}$$

for a biphasic T-wave;

defining T_R as T_{SLM} for a negative T-wave; and

defining T_R as T_{slm} for a positive T-wave.

18. The method according to claim **9**, further comprising computing a diastolic interval for the preset window using the depolarization tick time T_D for the preset window and an immediately previous repolarization tick time T_{R-1}.

19. A system for mapping cardiac repolarization activity, comprising:

a cardiac repolarization detection processor configured:

to receive an electrogram S(t);

to identify a depolarization tick time T_D using the electrogram S(t);

to identify a repolarization tick time T_R using either a point in time when S(t) passes below a preset threshold or local maxima and local minima of a first derivative S'(t) of the electrogram S(t); and

to compute a cardiac repolarization time period using the depolarization tick time T_D and the repolarization tick time T_R.

20. The system according to claim **19**, wherein the cardiac repolarization detection processor is further configured to compute a diastolic interval using the depolarization tick time T_D and a an immediately previous repolarization tick time T_{R-1}.

21. The system according to claim **19**, wherein the repolarization time period comprises an action potential duration.

22. The system according to claim **19**, wherein the repolarization time period comprises an activation recovery interval.

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