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Abstract

In general, the methodologies for cardiac electrical mapping entail registration of the electrical activation sequences of the heart by recording extracellular electrograms. The initial use of cardiac mapping was primarily to better understand the normal electrical excitations of the heart. However, the focus in mapping over time has shifted to the study of mechanisms and substrates underlying various arrhythmias; these techniques have been employed to aid in the guidance of curative surgical and/or catheter ablation procedures. More recently, the advent and continued development of high-resolution mapping technologies have considerably enhanced our understanding of rapid, complex, and/or transient arrhythmias that typically cannot be sufficiently characterized with more conventional methodologies. For example, the ability to visualize endocardial structures during electrophysiology procedures has greatly advanced the understanding of complex cardiac arrhythmias in relation to their underlying anatomy. In addition, such technologies provide powerful tools in the subsequent treatment of cardiac patients, particularly with the promise of accurately pinpointing the source of arrhythmias and thereby providing possible curative treatments. This chapter will summarize the most recent developments in catheter navigation and three-dimensional arrhythmia mapping technologies including both intracardiac and noninvasive approaches.

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32.1 Introduction and Background

The first recorded electrocardiogram (ECG) detailing the structure of atrioventricular conduction was made by Tawara nearly a hundred years ago [1]. Soon thereafter, Mayer was the first to observe rhythmical pulsations in ring-like preparations of the muscular tissue of a jellyfish (Scyphomedusa Cassiopeia) [2, 3]. In similar ring-like preparations of the tortoise heart, Mines was able to initiate circulating excitation by employing electrical stimulation [4]. Shortly thereafter, Lewis and Rothschild described the excitatory process in a canine heart [5], and after a delay due to the events of World War I, Lewis next reported the first real *mapping*

experiment in 1920 [6]. These groundbreaking studies were the first attempts to illustrate and document electrical reentry in an intact heart, and these results have greatly influenced those who have continued to perform mapping studies. Hence, the field of *cardiac electrical mapping* was established. Soon afterwards, the idea of mapping arrhythmic activation encompassed an ever larger number of studies, including the early pioneering work of Barker et al., who performed mapping of the first intact human heart in 1930 [7]. Many research groups have continued along this line of investigation, leading to several major discoveries in cardiac function as well as in the development of numerous systems to record such electrical activities in detail. One representative approach is the so-called body surface potential mapping [8], in which an array of electrodes is used to record and visualize the electrical potentials over the body surface. Much of the research performed to date has focused primarily on the mechanisms and substrates underlying various arrhythmias, and cardiac mapping has been employed to aid in the guidance of curative surgical and catheter ablation procedures [9–14]. More recently, the advent and continued development of high-resolution mapping technology has considerably enhanced our understanding of rapid, complex, and/or transient arrhythmias that cannot be sufficiently characterized with more conventional methodologies.

32.2   Conventional Methodologies

Currently, approximately ten million Americans annually are afflicted with cardiac arrhythmias (both ventricular and atrial), yet only a small percentage of these patients are expected to have electrophysiological (EP) mapping procedures. It is generally accepted that cardiac electrical mapping is critical in understanding the pathophysiological mechanisms that underlie arrhythmias, as well as the mechanisms that control their initiation and sustenance. Furthermore, cardiac mapping is commonly used for evaluating the effect of pharmacological therapies and directing surgical and/or catheter ablation procedures in the clinical EP laboratory.

Mapping of the depolarization and repolarization electrical processes is considered critical for the selection of optimal therapeutic procedures. In particular, mapping of potential distribution and its evolution in time is required for precisely determining activation patterns, locating specific arrhythmogenic sites, and identifying anatomical areas of abnormal activity and/or slow conduction.

In short, the purpose of such advanced clinical cardiac mapping techniques is to better characterize and localize arrhythmogenic structures, and this can be accomplished by a variety of different methods. Thus, *cardiac mapping* is a broad term that encompasses many applications such as body surface potential maps (BSPMs), epicardial mapping,

or endocardial mapping, as well as approaches including activation maps and/or isopotential maps. Such applications can be clinically applied via either invasive or noninvasive approaches. Nevertheless, there are many fundamental similarities in all of these techniques.

Currently, the gold standard is the clinical EP study, which is primarily used to: (1) determine the source of cardiac arrhythmias; (2) support the management of treatment through pharmacological means; and/or (3) support nonpharmacologic interventions such as implantable pacemakers, defibrillators, and/or ablation therapies (see also Chap. 28). More specifically, these methods are also used to assess the timing and propagation of cardiac electrical activities involving the 12-lead ECG and/or recordings of electrical activation sequences termed *extracellular electrograms*. These signals are obtained by using multiple intravascular electrode catheters positioned at various locations within the heart. The technique of catheter-based mapping not only permits a better understanding of the underlying mechanisms of various arrhythmias, but also serves as the basis for most of the emerging concepts for treatment, namely ablative techniques. Subsequently, the need for more invasive arrhythmia surgery (e.g., maze procedures) has significantly decreased as a result of advances in (and increased use of) these particular catheter-based endocardial mapping and ablation methodologies [15].

Nevertheless, the EP study is not without limitations. The electrophysiologist can only record electrical activity from electrodes located on the surface of the catheter, which must be in contact with the chamber wall. Such electrode areas (mm in diameter) are relatively small in comparison to the heart's total surface area. Thus, to adequately obtain complete global electrical activation patterns, it often dictates the placement of one or more catheters at multiple locations within the chamber of interest. As a consequence, this process requires a considerable amount of time, thus leading to extensive use of fluoroscopy and exposing the medical staff and patients to undesirable levels of ionizing radiation [16].

Secondly, and perhaps more importantly, fluoroscopy does not sufficiently provide for the visualization of the complex 3D cardiac anatomy and soft tissue characteristics of a heart's chambers (Fig. 32.1). As a direct result, the expedient and reproducible localization of sites of interest is often poor. More specifically, this inability to precisely relate EP information to a specific spatial location in the heart limits conventional techniques for employing ablation catheters for treatment of complex cardiac arrhythmias. Lastly, such techniques for mapping electrical potential activities from multiple sites do so sequentially over several cardiac cycles, without accounting for likely beat-to-beat variability in activation patterns. Despite these known limitations, electrophysiologists still use these conventional techniques as the "gold standard" for validation purposes.
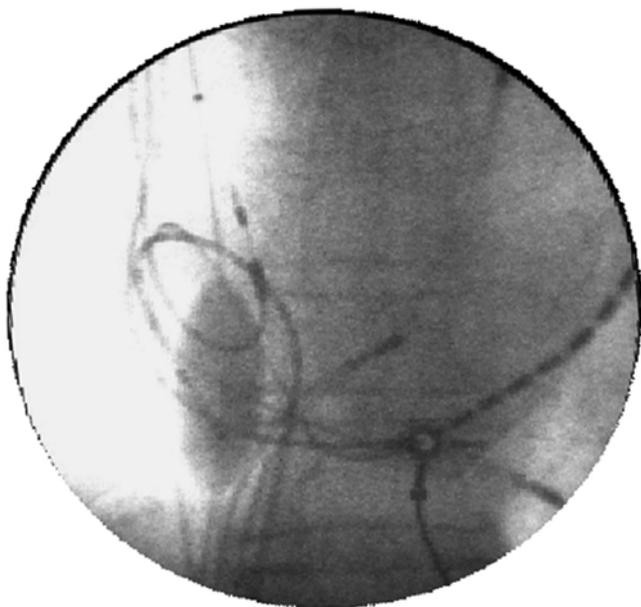
Fig. 32.1 Image illustrating fluoroscopy's poor soft tissue contrast

32.3 Recent Developments

In an effort to overcome the limitations associated with conventional EP mapping techniques, considerable advances have been made with both invasive and noninvasive imaging of cardiac electrical activity. More specifically, several high-resolution mapping technologies have been developed that can function in a complementary role to conventional mapping techniques, or they can be used independently. Moreover, it is now possible to integrate these techniques with imaging modalities such as magnetic resonance imaging, computed tomography, and real-time 3D ultrasound. These techniques can broadly be categorized into two primary technologies, each possessing unique advantages and disadvantages: *sequential mapping* and *continuous mapping*.

There are two distinct technologies that primarily comprise the first category (sequential mapping systems) including electroanatomical mapping systems such as the CARTO3® System (Biosense Webster, Diamond Bar, CA, USA), the EnSite Velocity™ System (St. Jude Medical, St. Paul, MN, USA), and the LocaLisa® system (Medtronic, Inc., Minneapolis, MN, USA). Common to each system is the capability to collect 3D locations as well as their respective electrogram recordings in the target cardiac chamber, to create an accurate picture of the heart's electrical sequence. A third mapping system that is ultrasound-based (Real-Time Position Management System, Boston Scientific Corporation, Natick,

MA, USA) was previously marketed but is not readily available, and will therefore not be described in this review.

Continuous mapping systems represent the second major mapping technology category, and typically consist of either basket or noncontact catheter mapping (NCM). Such systems allow for the recording of global data so that the rhythm can be characterized with a minimal number of cardiac beats. In general, basket catheter mapping technologies necessitate electrode contact with the chamber's walls in order to obtain sufficiently accurate reconstructed electrograms, whereas NCM simply needs to be placed in the blood pool of the chamber of interest. Yet, both methodologies overcome some of the limitations of fluoroscopy by allowing for the creation of accurate 3D intracardiac maps, hence providing new and unique insights on the specific diagnosis and treatment of complex arrhythmias. Examples of this technology category include the EnSite™ Array™ noncontact mapping catheter and system (St. Jude Medical) and the Rhythmia mapping system (Boston Scientific Corporation).

Recently, exciting advancements have been made in the field of noninvasive imaging such that cardiac electrical activities are spatially represented over the 3D space of the heart. He and coworkers have pioneered the development of 3D cardiac electrical activity from bioelectric recordings [17–19]. The goal of such cardiac electrical imaging, also known as the *inverse problem* of electrocardiography, is to noninvasively image and visualize the electrical activity of the heart from BSPMs. Due to the high temporal resolution inherent in these bioelectric measurements, the availability of bioelectric source imaging modalities provides much needed high temporal resolution in mapping functional status of the heart and, in turn, aids clinical diagnosis and treatment. In a series of studies, He and colleagues have developed data-driven 3D cardiac electrical imaging techniques that are based upon the fundamental biophysics of cardiac activation, to image activation sequences throughout the heart [20]; they further validated such an imaging approach in animal models using intracardiac mapping [21–24]. These rigorously conducted experiments demonstrate the ability to map transmural cardiac activation throughout the entire heart from noninvasive BSPMs. CardioInsight, Inc. has developed a revolutionary noninvasive electrocardiographic mapping platform (ECVUE™, Cleveland, OH, USA) that gathers information about the heart using a proprietary, multi-sensor electrode "vest" placed upon the patient's body. The system combines this electrical information with images from the patient's CT scan, to provide 3D maps of the electrical activity of the heart. Unlike conventional catheter-based mapping methods, the ECVUE system is noninvasive and provides a view of the entire heart's electrical activity during a single beat.

Fig. 32.2 CARTO® sequential mapping system (Biosense Webster, Inc.). Image from www.biosensewebster.com

32.3.1 Sequential Mapping Systems

32.3.1.1 Electroanatomical Mapping Technologies

Principally, electroanatomical mapping (EAM) refers to the integration of spatial data and temporal electrical data collected by catheters in contact with either the endocardial or epicardial surfaces of the heart. One such technology utilizes ultra-low magnetic field technology in order to localize the relative positions of mapping catheters in space and then to reconstruct 3D maps and activation sequences of the chamber of interest [25–27]. In short, the CARTO3® system uses one reference catheter (RefStar™), one mapping catheter (NaviStar™), and a pad that transmits three ultra-low magnetic fields (Fig. 32.2). Further, the amplifiers for the system are separate pieces of equipment that extract the information from the catheters and location pad, and then these data are sent to the workstation.

More specifically, three ultra-low magnetic fields are generated by coils in the locator pad positioned under the patient's bed. These ultra-low fields are detected by sensors in the distal tips of the mapping catheters, which are then positioned into the heart chamber(s) to be mapped under fluoroscopic guidance. Information within the magnetic fields such as amplitude, frequency, and phase of the field is subsequently used to determine the instantaneous spatial 3D position (x, y, and z axes) and temporal characteristics (pitch, yaw, and roll) of the catheter's distal tip location within a chamber. Catheters are then strategically placed at major anatomical landmarks (i.e., superior and inferior vena cava, tricuspid valve annulus, coronary sinus ostium, crista terminalis, and His bundle for a right atrium map) to serve as reference points for the subsequently derived electroanatomic map. Recordings of the 3D locations of the catheter tips (via a triangulation calculation) and correlating local electrical information from a multitude of points within the chamber are then sequentially recorded and used to reconstruct a 3D representation of the chamber.

After completion of the 3D reconstruction of the chamber's endocardial geometry, the timing of unipolar and bipolar electrogram signals, related to the fiducial point of the reference electrogram, allows for collection and display of activation times on the map in relation to the location of the catheter in the heart. To create the activation map, reconstructed locations on the map are typically color-coded, with red and purple representing the regions of earliest and latest electrical activation, respectively, and yellow and green showing the intermediate activated areas. Local activation times are then represented on a normal color scale sequence, where red is the earliest signal and purple is the latest recorded signal in reference to the chosen fiducial point. As a result, the sequential recording of different points by dragging the catheter along the endocardial walls of the chamber provides real-time, color-coded 3D activation maps.

A relative voltage map displaying the peak-to-peak amplitude of the electrogram sampled at each site may also be produced and superimposed on the reconstructed chamber. Using custom software, all maps can be shown in single or multiple views concurrently, with the capability to be rotated in virtually any direction. As described, a second catheter equipped with a sensor in its distal tip is also positioned in the chamber of interest, and is used to identify small changes in the mapping catheter's relative position that may have been caused by respiration and/or patient movement. Movement of the patient relative to the coils is continuously monitored by the system and the operator is notified to the need for repositioning, if the system detects relative motions beyond a set threshold. The most recent version (CARTO-3) allows the position of non-proprietary diagnostic catheters to be displayed on the system. For each specific magnetic location in space, the CARTO-3 system® registers the corresponding electrical current pattern emitted by the magnetic sensor-equipped mapping catheter. The position of conventional catheters can then be determined based on the detection of the current pattern emitted from each intracardiac electrode on the diagnostic catheter. However, it is still not

possible to process electrical information from these catheters for display on the virtual geometry.

Such EAM has experienced relatively widespread clinical use, and has also been utilized for the study of a variety of cardiac arrhythmias including: atrial fibrillation [28], atrial flutter [29–32], ventricular tachycardia [33, 34], and atrial tachycardia [35, 36]. One of the primary reasons for the success of this method lies in its capability to return an ablation catheter to any endocardial location on a previous map of the chamber without relying on fluoroscopy, i.e., with in vivo validation studies demonstrating that the location of the catheter can be determined with a high degree of accuracy using the system with mean distance error <1 mm. In most cases, the ablation catheter and mapping catheter are one and the same. This enables potential ablation target sites to be analyzed and treated in a single procedure, and provides the ability to precisely register the location of individual and/or linear lesions.

The reconstruction process using such a system can be generated in real time; however, due to the fact that this approach must sequentially acquire points, the process can be somewhat time-consuming [36, 37]; timing is governed by the number of points collected. Nevertheless, in practical use, the amount of the time required to reconstruct a chamber's geometry relies on the comfort level of the physician manipulating the catheter and the knowledge of the individual participating at the workstation. It should be noted that other potential limitations associated with EAM include the inability to simultaneously acquire maps of different heart rhythms [37], as well as the potential for inaccurate mapping due to movement of the patient and/or catheter. As a direct result, an unstable rhythm may prove too complicated to delineate and, therefore, may not be a primary indication for this technology.

32.3.1.2 LocaLisa® Technologies

Although no longer commercially available, the first technology developed for real-time 3D localization of intracardiac catheter electrodes within the chambers of the heart worked on the principle that when an electrical current is externally applied through the thorax, a voltage drop occurs across the internal organs, including the heart. This particular voltage drop can then be recorded via standard catheter electrodes and subsequently used to determine electrode positions within a given 3D space.

Using similar physical properties, the LocaLisa® system (Fig. 32.3) delivers an external electrical field that is detected via standard catheter electrodes. This is achieved by sensing impedance changes between the catheter and reference points. Analogous to the Frank lead system, the electric field is applied in three orthogonal directions (x, y, and z) with different frequencies (~30 kHz) via three applied skin electrode pairs. This system then records the voltage potentials

Fig. 32.3 The LocaLisa® mapping system (Medtronic, Inc.). Image courtesy of Medtronic, Inc.

detected by the catheter's electrodes within the three electric fields, thus allowing for a defined coordinate system to be created.

These voltage potentials are next translated into a measure of distance relative to a fixed reference catheter, giving the user a 3D representation of the catheter location within the heart's chamber. Important catheter locations are subsequently recorded and represented as color-coded spots on a 3D grid, a process that requires a skilled operator's interpretation (Fig. 32.4). Individual catheter locations can be saved, annotated, and revisited later in the procedure.

Due to the fact that the system displays real-time electrode movements, catheter movements due to cardiac and respiratory cycles are similar to those observed with fluoroscopy. In initial human validation studies, the LocaLisa® system was described to provide clinically feasible and accurate catheter locations within the heart [38]. Developers of the system reported successful use in over 250 complex ablation procedures for both ventricular and supraventricular tachyarrhythmias. The novel capabilities of this system included: (1) its ability to use any general catheter to collect data; (2) relative improvements in the visualization of catheters in 3D
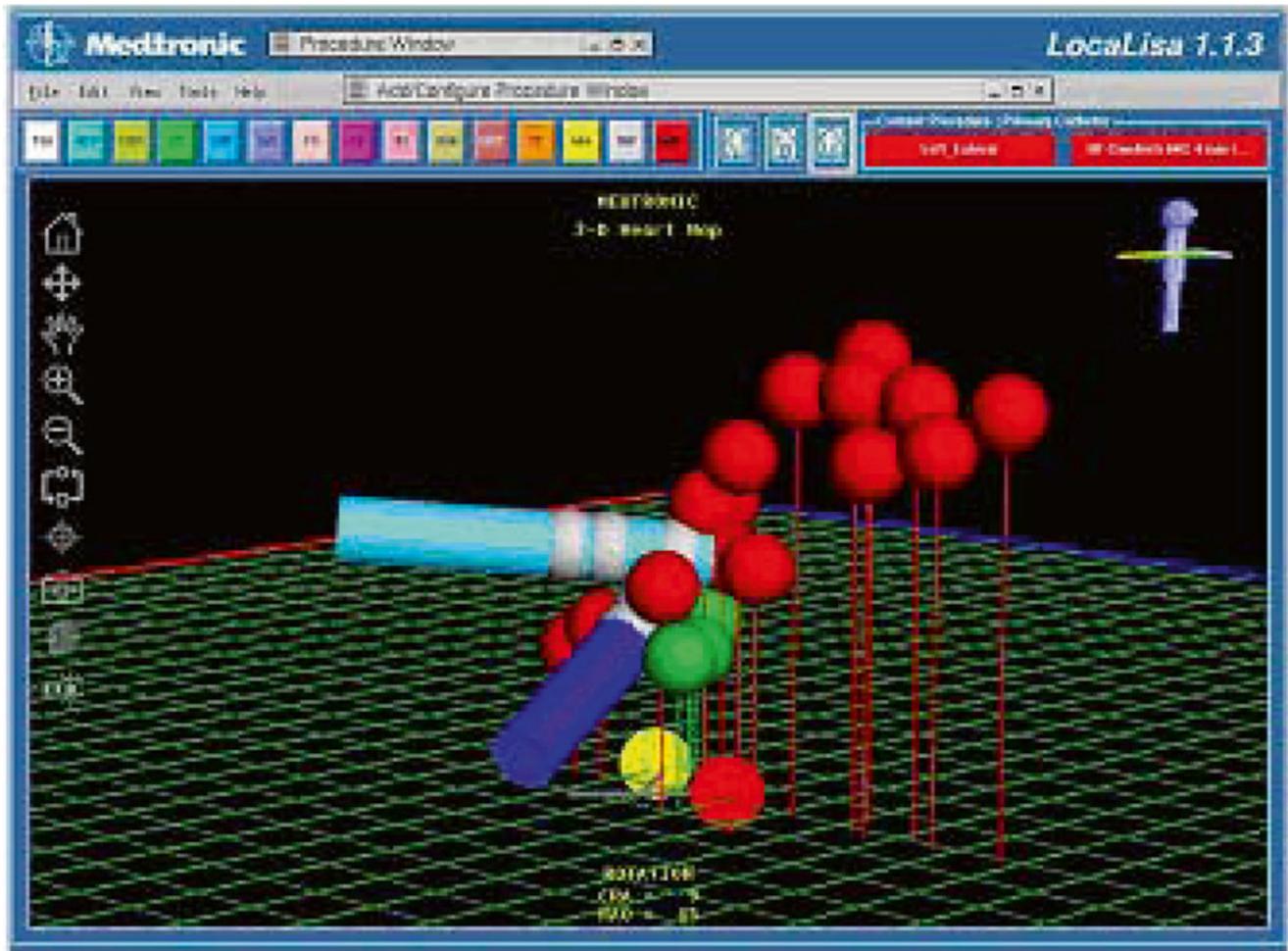
Fig. 32.4 Screen shot of LocaLisa®'s mapping software (Medtronic, Inc.). Image courtesy of Medtronic, Inc.

32.3.2 Continuous Mapping Systems

32.3.2.1 Basket Catheter Mapping Technologies

In general, the limited mapping resolution of conventional catheters may be greatly overcome via the use of a multielectrode basket catheter. Initial efforts to place multiple electrodes on a single mapping catheter were limited by electrode size. As such, basket catheter mapping was developed in the 1990s, and typical catheters contain 32–64 nickel, titanium, or platinum electrodes that are 1–2 mm long and 1 mm in diameter (Fig. 32.5) [41, 42]. Depending on the basket catheter shape and radius, the interelectrode distance can vary between 3 and 10 mm. Regardless, the accuracy in reconstruction of the chamber's geometry and electrical activity created by the basket system relies on: (1) the number of splines on the basket; (2) the number of electrodes on each spline; and (3) the percentage of those electrodes which achieve adequate contact with the endocardial surface. These multielectrode mapping catheters facilitate the creation of high-density maps, i.e., through the simultaneous collection

Fig. 32.5 Constellation® multielectrode basket catheter (Boston Scientific, Inc.)

space; and (3) a broad clinical applicability. Finally, this methodology could be applied with complex catheter designs such as multielectrode catheters, irrigated electrode catheters, and/or basket catheters [39–41].

of data from closely spaced electrodes. It should be noted that, due to specific anatomic features of the chambers that do not allow complete endocardial coverage by the basket catheter electrodes, the quality of contact of all the electrodes with the endocardium cannot be ensured, and thus it is common that some anatomic regions cannot be adequately mapped.

The initial use of basket catheters was reported in a number of animal studies which were aimed at characterizing either atrial [41] and/or ventricular arrhythmias [42]. More specifically, Triedman et al. [43] reported studies in which they utilized a Webster-Jenkins catheter (Cordis Webster, Inc., Baldwin Park, CA, USA) and a 5-spoke flexible ellipsoid with 25 bipolar electrode pairs for the mapping of right ventricular activation patterns. Data were obtained from catheters placed into the right atria and ventricles of juvenile sheep which were eliciting either normal sinus rhythm or acute and chronic pathological sequelae [43]. They concluded that employing a basket catheter had the potential to provide rapid, nearly real-time, activation sequence maps which improved their understanding of the mechanisms of complex reentrant tachyarrhythmias. Subsequently, Schalij et al., [44] reported on the first application of a basket catheter and resultant animation programs in 20 human patients with ventricular tachycardia. They reported that percutaneous endocardial mapping with basket catheters was feasible, of clinical value, and reasonably safe. Since then, basket catheter mapping has been employed in the study of numerous cardiac arrhythmias in various human populations [45–47].

Most recently, a novel multielectrode catheter and its integrated mapping system (Rhythmia mapping system, Boston Scientific) have been commercialized. The multielectrode mapping catheter (IntellaMap Orion™) has an 8 Fr profile and is equipped with a mechanism for bidirectional tip deflection. At the tip, there are 64 electrodes distributed on eight splines with an interelectrode spacing of 2.5 mm (Fig. 32.6). Electrodes can be used in either bipolar or unipolar configurations. The catheter is part of an integrated EAM system, which also includes an electronic patient interface unit and a computer workstation that is used to run the mapping software. Advanced front-end technology filters and collects high quality signals with low noise, and its open architecture allows the operator the freedom to choose and visualize most ablation or diagnostic tools. Further, the system's dynamic review capabilities allow the user to quickly review and edit data points; it also offers automated annotation to help minimize the time required to manually annotate data collected. The position of the multielectrode array is tracked utilizing a combination of magnetic and electrical field information. Initial preclinical feasibility was reported, demonstrating that the multielectrode catheter was capable of producing high-resolution electroanatomical maps of the

Fig. 32.6 Rhythmia mapping system's IntellaMap Orion™ high resolution mapping catheter (Boston Scientific, Inc.). Image from http://www.bostonscientific.com/en-US/products/capital-equipment--mapping-and-navigation/rhythmia-mapping-system/redefined.html

right atrium and the left ventricle in animal models [48, 49]. Average map acquisition times for the catheter (with continuous data collection) ranged from 5.2 to 9.5 min and these maps contained an average of 2753–3566 points.

Yet another technology has been commercialized that includes a 64 electrode basket (Topera, Inc., Menlo Park, CA, USA). The Topera 3D mapping system consists of the FDA cleared and CE marked RhythmView™ workstation and FIRMap™ panoramic contact-mapping tool, which are used in combination for the identification and localization of the sustaining mechanisms of cardiac arrhythmias such as atrial fibrillation, atrial flutter, atrial tachycardia, and/or ventricular tachycardia. The RhythmView workstation provides a graphical display of the right and left atrial electrical activities to assist in the diagnoses of arrhythmias and also to facilitate patient-specific atrial fibrillation treatment decisions. The FIRMap panoramic contact-mapping tool has been used to capture electrical potentials from the endocardium, which can then be used in conjunction with RhythmView to create activation maps to aid in the diagnosis of complex cardiac arrhythmias. The diagnostic tool ("basket") consists of 64 evenly spaced electrodes distributed among 8 splines. Images of both the RhythmView workstation and the FIRMap cath-

Fig. 32.7 RhythmView™ workstation and the FIRMap™ catheter. Image from http://www.toperamedical.com/patients/solution/

eter are shown in Fig. 32.7. To date, several reports have been recently published highlighting the clinical utility of this system [50–54].

It should be noted that there are limitations associated with basket catheter mapping. First, the use of a basket catheter that is too large or small compared with the relative dimensions of the chamber of interest will result in poor quality of electrograms in terms of morphology, stability, and relation with the given anatomic structures. Second, it has been cited that the relative movement between the beating heart and the electrodes can be detrimental to the electrical reconstruction process or may even cause irritation of the myocardium. Lastly, due to product size constraints, the basket catheter approach does not have the ability to map areas of the atrial appendage or pulmonary veins, which play major roles in the sustenance of atrial fibrillation.

32.3.2.2 Noncontact Mapping Technologies

Recently, NCM approaches have been more widely used in the clinical diagnosis and ablative treatment of complex cardiac arrhythmias, as described by Schilling et al. [12, 55, 56]. More specifically, the EnSite™ Array™ noncontact mapping catheter, used in combination with EnSite™ Velocity system (St. Jude Medical) introduced by Taccardi et al. [57], is comprised of a catheter-mounted, inflatable multielectrode array, a reference patch electrode, amplifiers, and a workstation (Fig. 32.8). The EnSite NavX technology is an open platform that is compatible with catheters from most manufacturers and can simultaneously display up to 12 catheters and 64 electrodes.

Specifically, this system's EnGuide® locator technology utilizes a single-use 9 Fr, 110 cm transvenous multielectrode array catheter (Fig. 32.9) consisting primarily of: (1) a polyamide insulated wire braid with 64 laser-etched unipolar electrodes; (2) a 7.5 mL inflatable polyurethane balloon; and (3) distal and proximal E1 and E2 ring electrodes. Additionally positioned on the proximal end of the catheter is a handle and cable connector that allows the physician to deploy a balloon in the chamber of interest, providing the electrical connection from the array to the patient interface unit of the system.

Typically, the multielectrode array is inserted transvenously into the patient's chamber of interest over a standard 0.032″ guidewire. Once positioned within a given chamber, the multielectrode array wire braid is mechanically expanded and the balloon is inflated using a 50/50 contrast-saline solution. Next, a second catheter, termed the *roving* catheter, is introduced into the same chamber of interest. Following connection to the breakout box, the system's EnGuide® technology emits a low 5.68 kHz signal via the tip of the roving catheter that is detected by the E1 and E2 ring electrodes on the multielectrode array catheter. Subsequently, by determination of the locator signal angles and strengths, the system is able to compute the 3D relationship of the tip of the roving catheter to that of the multielectrode array catheter ring electrodes. In order to reconstruct the 3D *virtual* endocardium of the chamber, the roving catheter continues to emit the 5.68 kHz signal as it is moved around the chamber by dragging the tip around the endocardial wall's contour.

A convex-hull algorithm is then utilized to omit the previously collected points that are inferior to the facets created during the collection process, so that the system essentially stores only the most distant points visited by the roving catheter (i.e., those from the endocardial surface during diastole).

Fig. 32.8 EnSite™ NavX™ navigation and visualization technology (St. Jude Medical, Inc.)
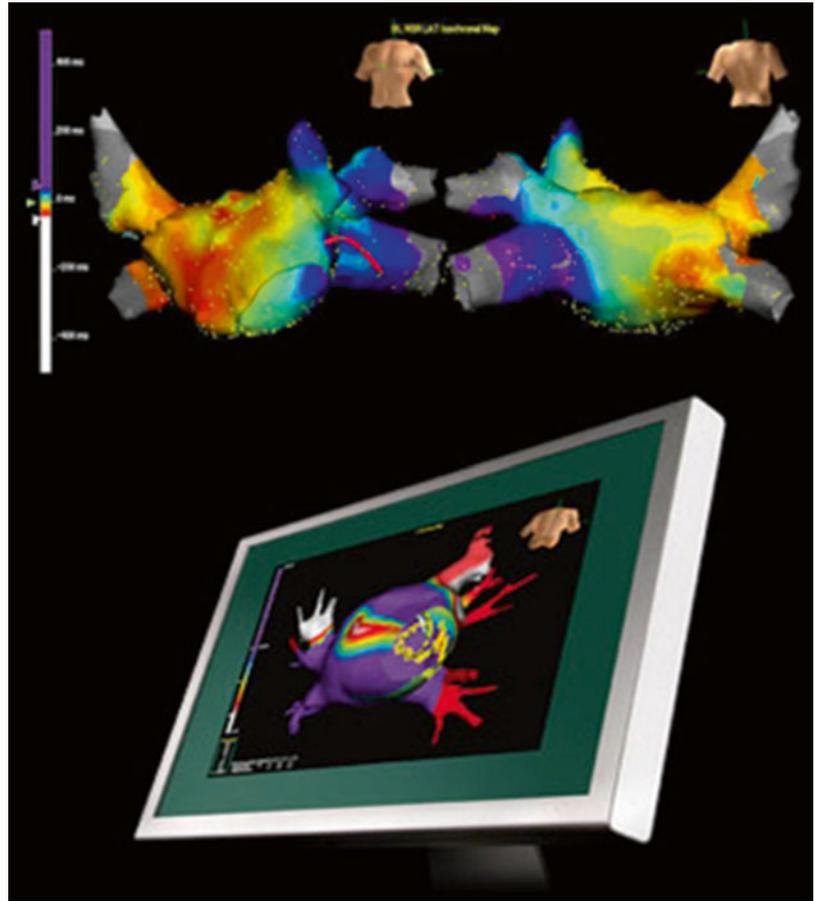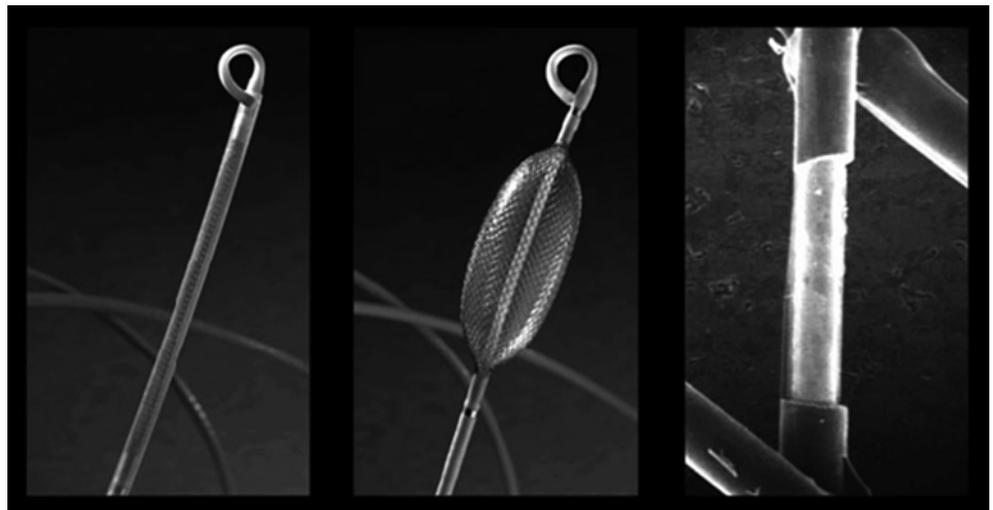

**Fig. 32.9** Multielectrode array catheter (St. Jude Medical, Inc.)

The roving catheter is used to locate the major anatomical locations associated with fluoroscopic imaging, and these anatomical landmarks are subsequently labeled on the reconstructed geometry to provide a frame of reference for the physician.

Once the geometry reconstruction is complete, the multielectrode array is used to detect and record the far-field intra-cavitary electrical potentials from the surrounding myocardium by employing an approximation method based on algorithms developed for inverse problems [58]. To further explain, the potentials in this field are typically lower in amplitude and frequency than the source potentials of the endocardium itself. Therefore, to improve accuracy and stability in reconstruction, a technique is used based on an

Fig. 32.10 Swine left ventricular (**a**) isopotential activation map and (**b**) isochronal activation map
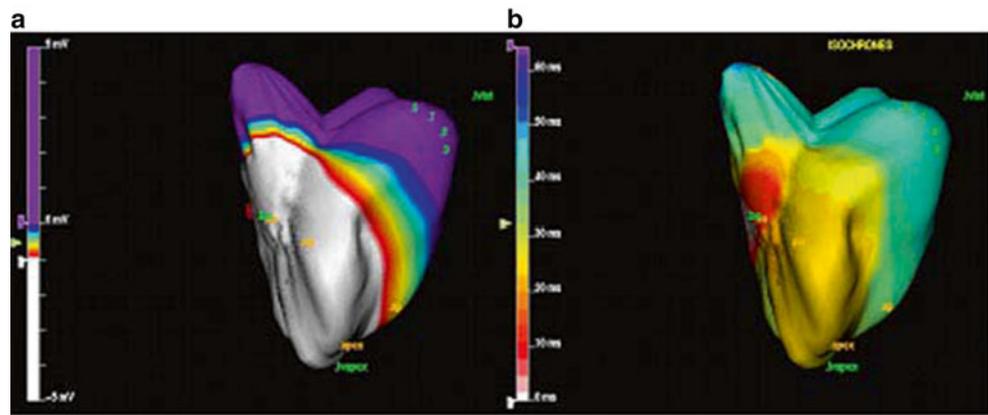
inverse solution to Laplace's equation by use of a boundary element method so that the resulting signals are used to reconstruct and display >3300 *virtual* electrograms.

After establishment of the chamber's voltage field, cardiac activation can be displayed as computed *virtual* electrograms or as *isopotential maps*. More specifically, these resulting isopotential maps are dynamic representations of the propagation of the electrical wavefront. As such, the electrophysiological information is visually represented by color coding that describes voltage, ranging from red (representing regions of depolarized myocardium) to purple (representing regions electrically neutral) (Fig. 32.10a). Additionally, the system allows for the creation of a static representation of the electrical propagations via *isochronal maps* (Fig. 32.10b). Consequently, the color-coded EP information is representative of the time required to activate different regions of the chamber. In cases where ablation is employed, the EnGuide® technology aids in navigating RF catheters to the appropriate site with an accuracy of ±1 mm.

The EnSite™ NavX™ EAM system is functionally very similar to the CARTO EAM but utilizes externally applied high frequency electric fields from cutaneous patches to determine catheter locations rather than magnetic sensors within the catheter tip. It requires three pairs of skin patches, one for each of *x*, *y*, and *z*-axes, thus creating a 3D coordinate system. Therefore, the NavX™ system can, in theory, be used to perform EP studies and catheter ablation procedures with a very low amount of fluoroscopy, which has been recently demonstrated with the introduction of the MediGuide™ system (St. Jude Medical) [59]. The MediGuide system is a visualization and navigation system that can display the relative positions and orientations of MediGuide Enabled™ devices (equipped with a MediGuide sensor) on both live and prerecorded fluoroscopy in real time. With the NavX™ software system, it is also possible to import a 3D reconstruction of anatomy taken from a high-resolution computed tomographic scan performed prior to the procedure; this is then synchronized to the images so that 3D images and maps can be manipulated simultaneously [60].

NCM has been utilized and validated in several clinical settings such as the evaluation and treatment of atrial flutter, atrial fibrillation [61–63], and/or ventricular tachycardia [64]. In such cases, this system has been used to aid in the identification of critical regions of slow conduction, to identify and then precisely return catheters to areas of interest in the chamber, and to subsequently visualize ablation lesion lines that have been created. Therefore, this system permits for the detailed reconstruction of global and local cardiac electrical events in a timely fashion within the EP lab. Most importantly, the system allows for a great deal of data to be recorded within the short duration of only one to two heartbeats, thus allowing the physician to adequately evaluate the origination, maintenance, and termination of nonsustained complex cardiac arrhythmias, pathways of reentrant activity, and/or electrical changes that may occur on a beat-to-beat basis.

Despite the vast number of advantages associated with NCM mapping, there are several current limitations worth noting. The NavX system has the disadvantage of not being able to specifically define the positions of given electrode (*x*, *y*, and *z* coordinates). Yet, the orientation of the catheter tip (pitch, roll and yaw) is not directly measured but can be partially inferred by determining the location of multiple electrodes along the path of a catheter. Background noise can greatly affect the quality of the recordings; this commonly originates from the surrounding environment or from the amplifier circuitry due to electrical fluctuations. In order to obtain optimally reconstructed electrograms, it has been documented that the distance from the area mapped to the multielectrode array should be less than 40 mm [55, 56, 65]; beyond this distance, there is an overall decrease in accuracy of the reconstructed electrograms. Additionally, the accuracy of the NavX system is adversely affected by heterogeneity in the electrical fields within the chest (i.e., different structures within the thoracic cavity have different electrical properties), which will reduce the accuracy of 3D localizations. NCM is only able to reconstruct the electrical activity on the endocardial surface of a given chamber, thus it is unable to

identify subendocardial activation characteristics which may play a critical role in the successful identification of various arrhythmias and, hence, the subsequent therapy employed. The dimensions of the multielectrode array when in full profile are 1.8×4.6 cm^2, which can restrict mapping catheter manipulation when placed in particular areas of the heart, such as right and left atrial appendages. Lastly, despite several software updates, the system is still complex and quite expensive.

32.4 Noninvasive Cardiac Mapping

Significant and innovative advancements have been made in the noninvasive imaging of cardiac electrical activity. Ongoing research in this area is aimed at improving our overall understanding of the mechanisms of cardiac function and dysfunction, in turn, aiding clinical diagnosis and management of cardiac diseases. Employing such an approach allows clinicians the opportunity to precisely localize the arrhythmic substrate and study mechanisms prior to the intervention by solving the so-called *inverse problem*. As a result, one can quickly focus therapy at the primary source of the arrhythmia and subsequently decrease the need for a lengthy EP procedure and, importantly, minimize fluoroscopy exposure to the patient and clinical staff.

The investigation of the epicardial potential inverse solution has garnered interest since the 1970s [66]. Recently the epicardial potential inverse solution has demonstrated the ability to reconstruct epicardial potentials in in vivo humans [67]. In addition, heart surface activation mapping, where activation maps over both the epicardial and endocardial surfaces are estimated from BSPMs, has been investigated [68].

Quite recently, He and coworkers proposed and developed the 3D cardiac electrical imaging (3DCEI) approach for noninvasively imaging 3D cardiac electrical activity employing BSPMs [17–20, 69]. In this 3D approach, cardiac electrical activity is estimated and visualized over the 3D myocardium by solving a linear or nonlinear inverse problem. This 3DCEI approach has been rigorously validated using 3D intracardiac mapping in rabbit [21, 70], swine [71], and canine models [22, 24].

The validation study of the 3DCEI in the swine model [71] is reviewed below, as the swine represents perhaps the most similar model to humans. In brief, a heart-excitation model and heart-torso volume conductor model were constructed based on preoperative MRI scans and prior physiological knowledge of the swine heart. The MR images were segmented to obtain detailed cardiac geometry and the cellular-automaton heart model. The entire heart excitation process could be simulated and the corresponding BSPMs were calculated by employing a boundary element method.

A preliminary classification system was also employed to initialize the parameters of the heart-excitation model, and then model parameters were iteratively adjusted in an attempt to minimize any dissimilarity between the measured and heart-model-generated BSPMs until the convergent criteria were satisfied. In this swine validation study, we employed site-specific pacing and, for each pacing site, both the 3D location of the initiation site for electrical activation and the corresponding activation sequence throughout the ventricles were noninvasively estimated using the above procedure. In total, data from 5 right ventricular and 5 left ventricular pacing sites from control and heart failure animals were collected and, subsequently, sequences of 100 paced beats were analyzed. It was demonstrated that the averaged localized error of the right and left ventricular sites was 7.3 ± 1.8 mm ($n = 50$) and 7.0 ± 2.2 mm ($n = 50$), respectively. The global 3D activation sequences throughout the ventricular myocardium were also derived. The endocardial activation sequences as a subset of the estimated 3D activation sequences were first compared with those reconstructed from simultaneously obtained data collected using an NCM system in order to validate the procedure. Figure 32.11 shows an example of the 3D activation sequence estimated from acquired BSPMs which were induced by ventricular pacing in a healthy animal. In addition to the heart-excitation-model-based approach [18, 19, 71], He and co-workers recently developed a data-driven imaging approach [20] and validated it in a series of animal studies [21–24], including pacing and ventricular tachycardia in healthy animals and animals with heart failure. These promising results suggest that the 3DCEI approach may, in the near future, provide a useful tool for both basic cardiovascular research and the clinical diagnosis and management of arrhythmias.

The ECVUE system (CardioInsight) is another noninvasive electrocardiographic mapping system under evaluation. The ECVUE system is built on the foundation of the Electrocardiographic Imaging (ECGI) technology. The ECGI approach was developed to reconstruct potentials of the epicardial cardiac surface to provide proximity to the heart's electrical sources and therefore have much improved resolution than the body surface potentials they are derived from (Fig. 32.12). ECVUE is considered as the first mapping system to combine electrical data from the body surface with heart-torso anatomy from a CT scan, to then calculate the 3D images of the electrical activity of a patient's heart. Importantly, due to the noninvasive nature of the system, it enables advanced cardiac mapping to be utilized outside the existing confines of the EP lab.

The physics of ECGI technology is based on a property that the electric fields generated by the beating heart within the passively conducting torso volume can be represented by the relationship: $\varphi_T = A\varphi_E$, where epicardial potentials (φ_E)

Fig. 32.11 Example of a 3D activation sequence imaged from noninvasive body surface potential maps in a control swine, following left ventricular pacing. Modified from [71]

32.5 Future Directions
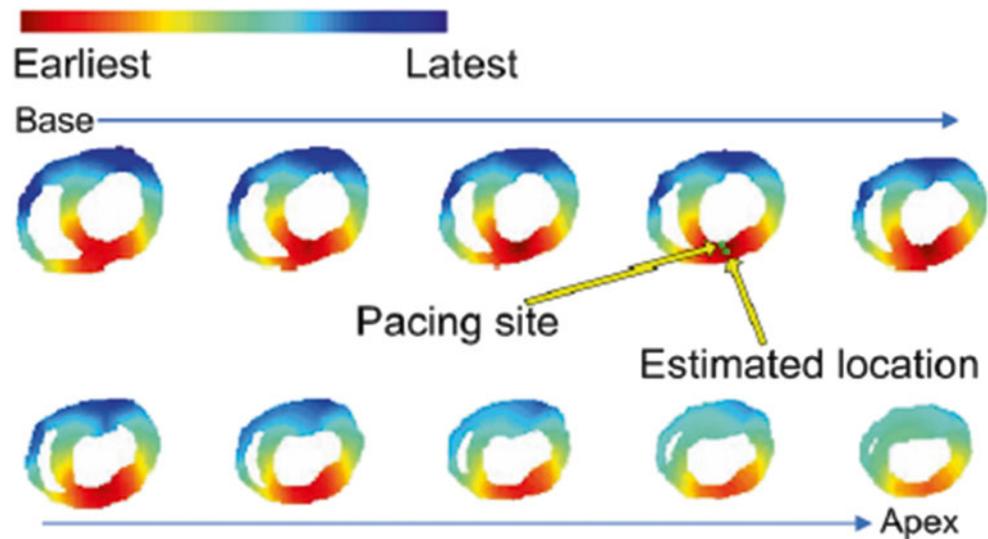
must be calculated from body surface potentials (φ_T) via a matrix (A) that approximates the electrical relationship between the surface of the body and the epicardial surface of the heart. A detailed description of these methodologies, as well as validation and practical considerations are included in various sources [72–78].

The ECVUE system is comprised of a single-use disposable 252 electrode vest, an amplifier system, and a workstation for advanced data analyses and visualizations (Fig. 32.13). The vest was designed to accommodate a variety of torso shapes and sizes [79]. The system received its CE mark in 2011 and has been used in over 1000 clinical cases for mapping either atrial tachycardia or fibrillation and thus in support of patients undergoing cardiac resynchronization procedures. To date, the system has been used particularly in patients with intermittent, unstable, transient, and polymorphic arrhythmias, and also in cases where the attributes of the system in providing single beat, dual chamber (bi-atrial or biventricular) global mapping information was perceived as a distinct clinical advantage. The aggregate clinical success or performance use of the ECVUE (compared to an EP study) approach ranged from 85 to 100 % for a given chamber or region of interest within the cardiac chamber. Further, it is considered that use of the ECVUE system has specific advantages in patients with: (1) complex arrhythmias, including polymorphic arrhythmias; (2) complicated congenital cardiac anatomies; and/or (3) fibrillatory arrhythmias. It has been reported that the noninvasive mapping information provided by the ECVUE system was especially useful in facilitating EP diagnoses with lower amounts of catheter manipulation; recent literature relating to the use of the system is included in other sources [80, 81].

The mapping technologies developed and employed to date have revolutionized the clinical EP laboratory, and their use has led to numerous novel insights into the mechanisms underlying all types of arrhythmias. Relative to the multicatheter approach, such technologies have improved resolution, 3D spatial localization, and/or rapid acquisition of the detailed characteristics of cardiac activation in both normal and diseased hearts. In general, these technologies employ novel computational approaches to accurately determine the 3D location of mapping catheters and anatomic-specific local electrograms. Acquired data of the relative intracardiac catheter position and recorded intracardiac electrograms are commonly used by such technologies to reconstruct, in real time, a representation of the 3D geometry of the cardiac chamber of interest.

Nevertheless, to date, such mapping systems are relatively expensive and generally not required for the diagnosis of more common clinical arrhythmias such as atrioventricular nodal reentry, accessory pathway mediated tachycardia (Wolff–Parkinson–White syndrome and concealed pathways), or typical atrial flutter. Furthermore, it should be noted that other emerging technologies, such as intracardiac echocardiography, and the incorporation of high-resolution imaging modality datasets (such as CT or MRI) are considered useful adjuncts for more precise and rapid catheter positioning, perhaps even providing more reproducible catheter positioning towards specific intracardiac structures that are more difficult to identify for mapping or ablation. Yet, the mechanistic contribution of the newer cardiac mapping systems to treat various arrhythmias is likely to be well substantiated. Despite the theoretical clinical advantages highlighted by the technologies discussed in this chapter, further
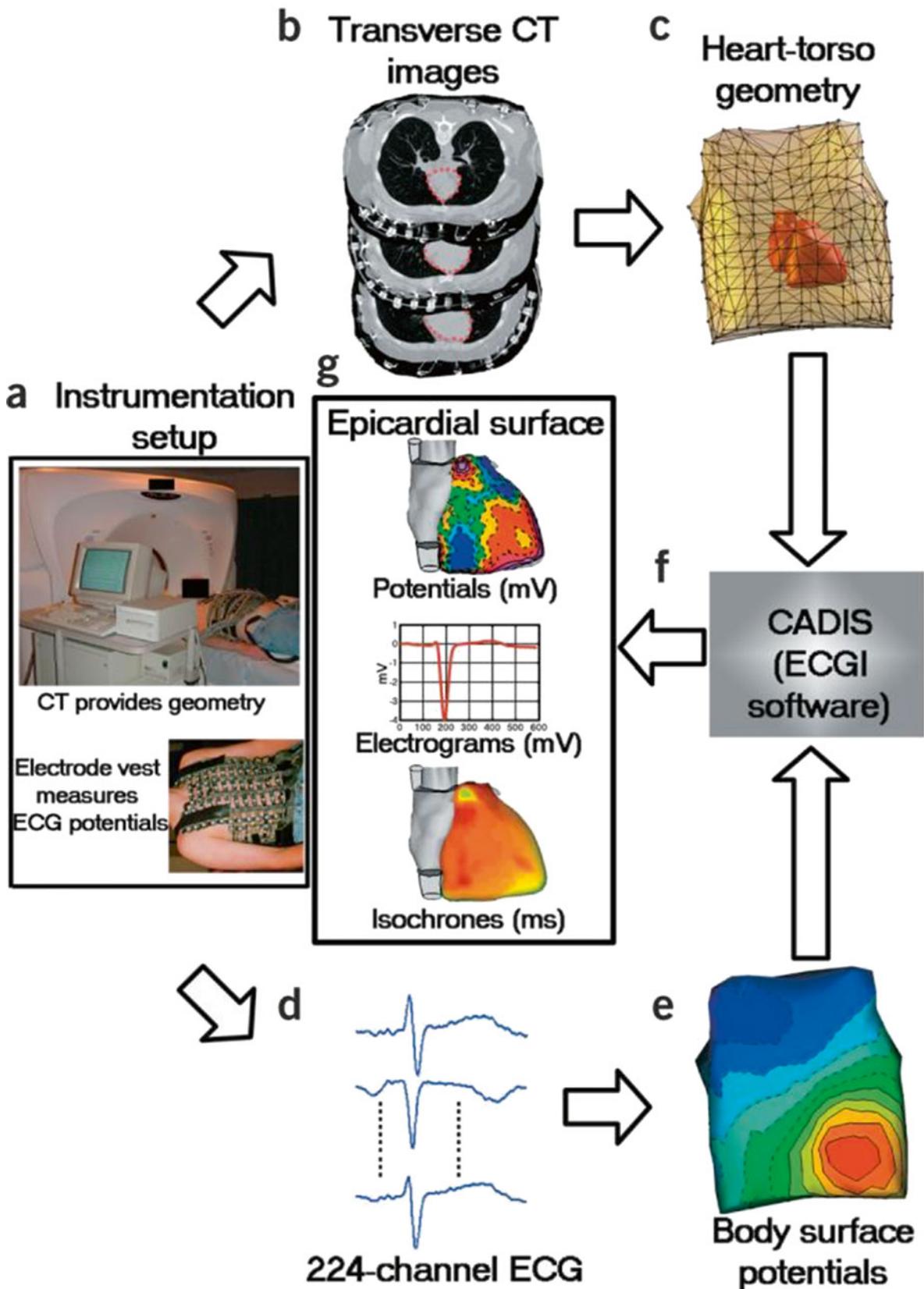
Fig. 32.12 Block diagram of the ECGI procedure. (**a**) Instrumentation setup, (**b**) Computed tomography slices showing heart contours (*red*) and body-surface electrodes (*shiny dots*), (**c**) Meshed heart-torso geometry, (**d**) Sample ECG signals obtained from mapping system, (**e**) Spatial representation of body surface potentials, (**f**) ECGI software package (CADIS), (**g**) Examples of non-invasive ECGI images, including epicardial potentials, electrograms, and isochrones

Fig. 32.13 ECVUE system and non-invasive vest. Image from http://www.cardioinsight.com/product/the-ecvue-vest-at-work/
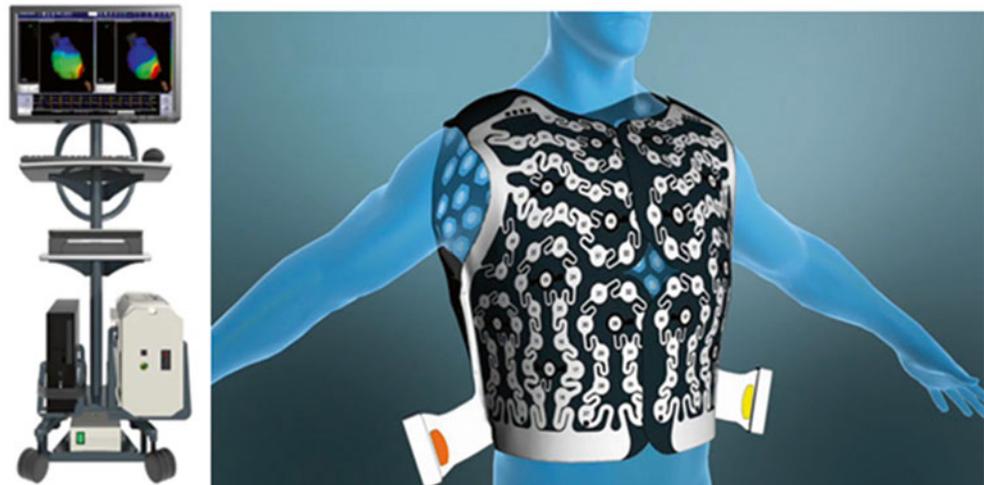
prospective human clinical trials will ultimately need to be performed to provide validation of optimal clinical utility.

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