Virtual Reality in Interventional Electrophysiology

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There are 2 principal components to any cardiac intervention: definition of the shape, location, and functional anatomy of a target and precisely located delivery of therapy. As tools for catheter-based electrophysiological (EP) intervention become more potent, it is important to ensure that the technologies used to visualize the target and guide their application are of comparable power. In the digital era, these visualization technologies provide us with a virtual image of the heart. Ideally, this image should be a perfectly accurate, easy to generate, fully transparent to the user, and immediately available for real-time navigation. One approach to understanding the value and appropriate uses of such tools is to assess the degree to which they meet these criteria. Articles in this issue of Circulation by Ector et al and Sra et al seek to address this task; they document the independent and parallel development a novel approach to anatomic visualization in EP intervention combining fluoroscopy and volume imaging of the heart.

Traditionally, navigation of catheters for EP study has been performed with fluoroscopic guidance. Fluoroscopy provides a flattened and distorted representation of cardiothoracic anatomy, but the use of multiple projections by a skilled operator allows understanding of anatomy and catheter location in remarkable spatial detail. Building on experience earned over decades of diagnostic catheterization, fluoroscopy has provided excellent and instantaneous feedback for EP catheter manipulation, sufficient to have permitted the development of the field of catheter ablation. This developmental process was facilitated by the serendipitous fact that, for many common arrhythmias, important procedural landmarks such as the His bundle and mitral groove may be identified on fluoroscopy by placement of catheters in easily and visibly reproducible locations.

Because fluoroscopy provides a direct, unmodified, and immediate view to the operator, there is no simple way to organize multiple measurements taken from a roving catheter into a more permanent and clinically useful model of cardiac electrical activity. This shortcoming became important as interventional electrophysiologists began to move away from

the AV groove and its landmarks. Catheter ablation proved to be feasible for complex atrial and ventricular arrhythmias, but its efficacy in these arrhythmias is considerably lower than that achieved for AV nodal reentrant tachycardia and AV reciprocating tachycardias, in part because of difficulties in target localization. Except for the common form of atrial flutter, reentrant atrial and ventricular arrhythmia circuits are unconstrained by cardiac landmarks easily identified with fluoroscopy. Similarly, modern approaches to ablation of atrial fibrillation are contingent on detailed, patient-specific knowledge of proximal pulmonary venous anatomy, information also not easily extracted from fluoroscopy.

Research in experimental EP and clinical arrhythmia surgery has demonstrated the enormous power of mapping as a methodology: the imposition of a spatial frame of reference on the heart to characterize the activation sequence. Clinical investigators demonstrated that even rough, ad hoc assignment of electrogram timings to approximate locations on anatomic cartoons are sufficiently accurate to allow the formation of useful, general hypotheses regarding arrhythmia mechanism (eg, the work by Cosio et al). The potential for more powerful and refined approaches to mapping in the EP laboratory was clear. Over the last decade, several competing technologies have been developed to enhance our ability to visualize, map, and navigate in the 3D anatomy of the heart. They share the common feature of providing a physically accurate and detailed spatial frame of reference, a field that grids the area of interest in the heart with unique values of electromagnetic, electric, or ultrasound energy that can be detected by the catheters and allow physically accurate localization of the catheter. By iterative recording of its location, the position of which is (hopefully!) always bounded by the endocardial surface, one may gradually build a virtual representation of the chamber being mapped.

The reports published in this issue of Circulation document the feasibility and development of catheter navigation and mapping by fusion of fluoroscopy with cardiac volume images derived from multislice CT and MRI. These techniques are different than those described above. First, fluoroscopy remains the means by which the catheter is navigated from moment to moment; a secondary technology is not superimposed on the procedure itself. Second, in these studies, the shape of the cardiac chamber to be mapped is predefined in the imaging suite and is not dependent on catheter movement. Rather than creating a virtual cardiac anatomy from recorded catheter movement, these techniques seek the accurate registration that predefined volume image with fluoroscopic data obtained in the catheterization laboratory. Sra et al have used CT scanning of the left atrium to identify the locations of the proximal segments of the pulmonary veins. After experimental trials in phantom models demonstrated a mean location error of 1 to 2 mm, a

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clinical trial of this approach was used and qualitatively showed visual concordance between the predicted and observed local anatomy of the pulmonary veins. Ector et al investigated the use of MRI for construction and fusion of right atrial anatomy. Their somewhat more quantitative approach demonstrated excellent concordance between the heart model used for testing and the reconstructed 3D model used for fusion, with negligible errors (<0.5 mm) observed after alignment of the heart model with its fluoroscopic projection. Somewhat larger errors (mean, 1 to 2.5 mm, with maximal errors ranging from 3 to 10 mm at various measured borders) were noted during the fusion of real atrial images with clinical angiographic studies, allowing inference of the magnitude of additional error arising from cardiorespiratory motion. These values are of a magnitude and type comparable to those seen with other nonfluoroscopic mapping technologies. It is important to note that these results, while slightly disparate, are not directly comparable and that the small differences may be due to differences in methodology.

These measured errors point to the weaknesses and limitations of 3D imaging for anatomical mapping that may limit their application: Spatial accuracy is not the same thing as anatomic accuracy. An important assumption generally made by researchers in this field is that a ground truth exists against which these types of visualization tools may be evaluated. Specifically, all such tools currently in use represent the mapped chamber as a static object. A future exception may be mapping systems based on echocardiographic imaging, but real-time fusion of these images with electrical data has not yet been reported. Sra et al specifically state the assumption in their registration algorithm that the cardiac chambers are treated mathematically as “rigid bodies,” ie, objects that can be scaled, rotated, and moved but whose shape remains fixed. This is also implicit in Ector et al’s approach. Gating to the cardiac cycle may reduce spatial errors arising from the normal systolic and diastolic changes in chamber size and position. However, there are also significant variations in chamber size and geometry related to phasic changes in intrathoracic pressure and volume, heart rate and filling pressures, and the possibility of distortion induced by endocardial catheter pressure. Finally, uncompensated patient movement may degrade the quality of the registration of image and reference system. Although the concept of an anatomic benchmark may be of great value to the development of these technologies, it is not clear that it can serve as an indicator of the anatomical “truth” of the virtual image presented to the operator, as a predictor of clinical utility, or as a basis for comparison of competing technologies.

A common feature of all new visualization technologies is that they tend to induce an “Aha! Now I can see it!” reaction in early use. There is no doubt that these systems can provide unprecedented clarity of association between anatomy and arrhythmia mechanism and represent a revolutionary advance in our ability to intervene on the heart with greater sense of understanding. In legal Latin, res ipsa loquitur (the thing speaks for itself). However, the enthusiasm that comes with seeing the heart in a new way may bias us to looking for data that tend to support rather than question the validity of the innovation that enables it. For this reason, we should ask ourselves, What is the best way to evaluate these systems academically?

In the EP literature, initial evaluation of new visualization tools has typically consisted of an engineering evaluation of system performance on the bench, which defines the accuracy of the system because of the limits of the technology itself. This is closely followed by feasibility studies in animal models and/or humans to determine estimates of some ad hoc measure of spatial error. This is the pattern adopted by the 2 articles reviewed here. Little and perhaps insufficient attention is paid to identifying the potential sources of error and conditions leading to worst-case scenarios. A good counterexample is the approach of Reddy et al. In a recent article discussing developmental work done on image fusion of electroanatomic maps and volume imaging, they explored some of the specific conditions under which their approach failed to provide appropriate image registration and, from this, were able to modify and improve their algorithms.

Once systems come into clinical use, clinical studies that document their utility in practice emerge. Early reports are often dominated by images rich in novelty that emphasize the power of a new view of the heart, followed by case series demonstrating specific uses of the new visualization tool in specific arrhythmias or anatomies. However, the clinical utility of these systems must in the end be proved by how well they guide the delivery of therapy, usually ablative. Therapeutic end points often have several inputs; consequently, assignment of causal effect is more difficult. Ablation is itself a spatially uncertain process, and beyond some threshold, further improvements in accuracy of visualization may not be clinically relevant because of our inability to control the size and shape of the ablation lesion with enough precision.

If there is no clear clinical indicator of what constitutes the best practice of interventional EP with regard to visualization tools, nonclinical factors will determine their adoption: cost, ease and speed of use, operator preference, availability of appropriate support and ancillary imaging services, and the inertial effect of prior training, experience, and capital investment that represent the installed base of the technology. Thus, structured clinical outcome studies are critical for evaluation of these technologies, but this category remains only thinly populated in the mapping literature. Most clinical outcome studies to date have been done in arrhythmias such as supraventricular tachyarrhythmia and atrial flutter, which are already treated with high success rate with fluoroscopy and thus may not be the most useful basis for comparison. Some have suggested improved outcomes with advanced visualization technologies, but most have demonstrated substantial clinical equivalence between them and the use of fluoroscopy alone, with their principal demonstrable benefits being the anticipated reductions of fluoroscopy exposure and possibly procedure time.

When an enabling technology expands the indications for ablation to include arrhythmias for which good alternative approaches appear to be nonexistent, it is sometimes argued that it would be unnecessary, too difficult, and possibly unethical to perform controlled studies of clinical outcomes. In this case, this contention seems unsupported by the small
amount of preliminary data currently available. Whatever the visualization technology used in EP procedures, it remains appropriate to hold a skeptical academic perspective on the adverse potential of these systems for inaccuracy and possible absence of incremental clinical utility over standard techniques. It is critically important for the users of such systems to recognize virtual reality in interventional EP for what it is—an exciting tool of both enormous value and promise, and also subtle limitations, that needs to be applied carefully and intelligently to help patients.

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References

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