Noninvasive electrocardiographic imaging through body surface potential (BSP) mapping and mathematical inverse procedures represents a novel and emerging technology that enables estimation of myocardial depolarization and repolarization. As such, this mapping approach offers the possibility of not only facilitating therapeutic catheter interventions for a variety of cardiac arrhythmias, but also of helping to define the underlying electrophysiological mechanisms of certain cardiac arrhythmias and to perhaps even guide cardiac resynchronization therapy and optimization.\(^1,2\)

Although this mapping strategy merely estimates the time course of unipolar epicardial potentials, the latter is capable of providing substantial information regarding intramyocardial activation.\(^3,4\) The currently available BSP mapping systems allow incorporation of data using a greater number of electrodes than before, yielding preprocedural arrhythmia localization using only a few or a single heartbeat. The mean resolution of the currently used noninvasive electrocardiographic imaging techniques is \(\approx 1\) to 2 cm, though some investigators have reported better results.\(^2,5\) Aside from their noninvasive feature and ability to be applied at bedside, current BSP mapping technologies also permit 3-dimensional integration with computed tomography or magnetic resonance imaging modalities. The initial experiences using this innovative mapping approach have demonstrated improved efficacy and reduced procedural duration.\(^6\)–\(^8\) Furthermore, a noninvasive electrocardiographic imaging system (ECVUE; CardiInsight Technologies, Inc) was recently approved for clinical use in Europe. Yet, despite multiple encouraging reports and experiences, this imaging technique has not quite evolved into daily clinical practice, perhaps due to limited data availability, insufficient validation, and complexity of the mathematical models underlying the applied inverse procedures.

The initial recording of human BSPs was reported by Waller in 1887, with a capillary electrometer that he used to systematically investigate the potential distribution associated with the beating heart.\(^9\) Subsequently, Einthoven published the first surface ECG in 1903, constructed using the string galvanometer.\(^10\) Nearly a century later, alternative configurations based on the recording of potentials from a large number (32 to 256) of torso electrodes using a multielectrode vest were proposed.\(^11\) However, the latter has not been systematically incorporated into daily clinical practice due to uncertainty surrounding its clinical utility. In the meantime, much experience has been gained with interpretation of the 12-lead ECG, which remains the gold standard in clinical cardiac electrophysiology. Nevertheless, there are inherent limitations to the use of the 12-lead ECG. Multiple electrocardiographic algorithms have been proposed to predict the activation site of various cardiac arrhythmias, but accuracy and consistent reproducibility have been lacking.

A major limitation has to do with the spatial resolution afforded by the 12-lead ECG. Also, alterations in the heart’s anatomy and orientation within the chest with variable precordial lead placements can yield conflicting results. Therefore, a definitive diagnosis typically requires an invasive approach.

In contrast, the recent development of robust inverse procedures has kindled renewed interest in utilization of BSP mapping. Although the forward problem of electrocardiography refers to the estimation of BSPs from those measured on the surface of the heart, the inverse problem implies the contrary.\(^12\) Through an inverse procedure, the potentials on the epicardial surface and myocardial activation times are estimated using the recorded BSPs as source data. To determine cardiac activation times, the potentials generated by cardiac electrical activity within the torso volume need to be modeled. Unlike the forward problem, which may be solved uniquely, the inverse problem is not unique with regard to

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whereas the VCM attempts to reproduce the in
simply represented as an electrical current generator,
(VCM). In a biophysical source model, the heart muscle is
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most inverse procedures use a combination of 2 models: a
biophysical source model and a volume conductor model
(VCM). In a biophysical source model, the heart muscle is
simply represented as an electrical current generator,
whereas the VCM attempts to reproduce the influences of
different tissue types within the thoracic cavity on the
potential waveforms. To reproduce such an effect, a detailed
anatomical model of the patient’s chest incorporating the
conductive properties of thoracic structures is, in fact,
required. Such anatomical data can be derived from a
computed tomography or magnetic resonance scan.

In this issue of the journal, Bhagirath et al15 reported their
findings on noninvasive electrocardiographic imaging (inverse
potential mapping using 62 recording electrodes) guided by
magnetic resonance–derived VCMs, creating both homoge-
neous and nonhomogeneous models. It should be pointed out
that the principal difference between homogeneous and
nonhomogeneous models consists of the latter additionally
taking into account the specific conductivity values for the
lungs (0.04 S/m). The most commonly used noninvasive
mapping technique typically uses a homogeneous VCM, and
other investigators have shown sufficient accuracy associated
with the use of computed tomography–derived models16,17.
However, in their study, Bhagirath et al emphasized the
significance of magnetic resonance–guided nonhomogeneous
VCMs. The authors advocated for integration of adjacent
organs and their specific impedances, particularly in those
with a high body surface area, myocardial infarction, or
pulmonary edema. As such, they argued that the aforemen-
tioned circumstances can meaningfully influence BSPs and,
consequently, the data due to alterations in conductivity and
resistivity. Briefly, their study included 3 healthy volunteers
and 8 symptomatic patients with frequent ventricular ectopy.
Using this approach, it was possible to estimate—with great
accuracy—the locations of the sinoatrial node and/or
ventricular arrhythmia foci using a single ectopic beat.
Although this study was based on a small sample size, the
authors illustrated a difference in accuracy with inverse
potential mapping using homogeneous versus nonhomoge-
neous VCMs, in favor of the latter. In 2 of 8 patients, there
was no difference in localization between homogeneous and
nonhomogeneous VCMs. However, homogeneous VCM was
associated with a notably greater difference (≥2 mm) in
localization in 5 patients, whereas in another patient, the
focus could not even be identified. It should be emphasized
that these differences were judged exclusively by the site of
ablation as marked on the 3-dimensional electroanatomical
mapping system (EnSite, St. Jude Medical, Inc), which itself
could have inherent inaccuracies. Nonetheless, this study
provides important and relevant insights into the clinical
implications and applicability of magnetic resonance–guided
inverse potential mapping in patients with idiopathic
ventricular arrhythmias. The findings of this study suggest
that implementation of such an approach may offer several
crucial benefits including improved ablation planning as a
result of preprocedural identification of the arrhythmia focus,
reduction of procedural duration and radiation exposure, and
possibly improvements in ablation efficacy among patients
presenting with reduced arrhythmia burden and/or multifocal
arrhythmias.

Although certain advancements such as real-time panora-
ic mapping and improved signal processing will likely help
enhance the current state of this technology, a potential
weakness of this approach is that it derives its diagnostic
information from reconstructed electrograms on the epicardial
surface of the heart. Although a recent report18 has shown a
close correlation, the endocardial sequence of activation will
not always be identical to the epicardial activation sequence.
Furthermore, because the septum is not an epicardial struc-
ture, direct mapping of the septum is also not possible.
Instead, localization of a septal focus would have to be
deduced through indirect analysis and timing of the epicardial
breakthrough activation sequence. Lastly, suboptimal detec-
tion of arrhythmia activation from the corresponding cardiac
chamber needed for accurate analysis can also pose a source
of limitation with regard to noninvasive electrocardiographic
mapping. This becomes relevant in situations in which the
atrial activation may be obscured within the inscription of the
ventricular activity, as in the case of an atrial tachycardia with
2-to-1 conduction to the ventricles. To effectively permeate
into the clinical cardiac electrophysiology arena, the physical
validity of the simulations and the strength of the methodolo-
gies must be undisputed. To satisfy this condition, addi-
tional knowledge about the challenges regarding the use of
inverse potential mapping seems imperative. In addition,
high-resolution imaging techniques and improved inverse
algorithms should be developed and further integrated.

In summary, noninvasive electrocardiographic mapping of
cardiac excitation has recently become the primary focus of
active and ongoing research. Although this technology holds
great promise and will likely evolve to complement the
conventional mapping techniques currently used in cardiac
electrophysiology, it has not yet emerged as a clinical tool.
that is usable in day-to-day practice. This has largely been due to
technical challenges in recording, processing, and interpreting
the data. Moreover, clinical validation with respect to
various arrhythmia mechanisms is still needed. The study by
Bhagirath et al greatly exemplifies critically needed research
to further enhance noninvasive electrocardiographic imaging
and to help create utility for such a technology in clinical
practice.

Disclosures
None.

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