Three-Dimensional Representation of Atrial Anatomy and Electrophysiology Enhanced by Mixed Reality

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Abstract

Teaching cardiac anatomy and electrophysiology involves conveying complex three-dimensional (3D) structures, which is pivotal for understanding the ECG genesis.

The P wave morphology is affected by multiple factors, including the sinoatrial node location and extent, and points of myocardial capture. For three exemplary ECGs extracted from the PTB-XL database - normal, inverted / negative and an interatrial block (IAB) P waves, we performed CineECG analysis on a highly detailed generic anatomical atrial model. We qualitatively evaluated SAN exit points locations and corresponding activation trajectories and sequences. The results were exported into the mixed reality Hololenses 2 system for enhanced visualization.

As expected, normal and negative P waves were found to feature superior and inferior SAN capture points with top-down and down-top average activation trajectories, respectively. The considered IAB provided a markedly distinct excitation pattern with the right-left pattern. These differences were further highlighted by visualising the complex electro-anatomical interplay of cardiac excitation in the immersive mixed reality environment.

This work presents novel mixed reality 3D visualization options for atrial anatomy in high spatial resolution augmented by the respective P wave genesis.

1. Introduction

Teaching cardiac anatomy and electrophysiology requires explaining complex 3D structures and dynamic processes essential to understanding cardiovascular function and disease. A key component of this is learning about the electrocardiogram (ECG) and its connection to heart anatomy, which is crucial for diagnosing cardiac pathologies. Traditional methods such as lectures, textbooks, and cadaveric dissections offer foundational knowledge but have notable limitations. Lectures often provide passive learning, which may not fully engage students in real time. Textbooks and atlases offer detailed visuals but struggle to convey the dynamic nature of heart processes. While cadaveric dissections provide hands-on experience, they lack insight into the heart's electrical conduction system. Physical models, such as 3D-printed hearts, improve visualization of patient-specific anatomy but do not fully address these gaps. Clinical training, particularly through ECG interpretation, remains essential for identifying waveforms and their clinical significance.

Modern approaches, including problem-based learning (PBL), simulation software, and extended reality (XR) technologies such as virtual reality (VR) and mixed reality (MR), have greatly enhanced the learning experience. PBL fosters deeper understanding by presenting clinical scenarios that develop critical thinking, although its effectiveness depends on the design of the problems. Simulation software for electrophysiological mapping allows students to visualize and manipulate cardiac electrical activity, simulate pathological conditions, and link them to ECGs, though it requires a strong technical foundation [**?**]. Extended reality (XR) technologies, particularly virtual and mixed (VR and MR), create immersive environments that enhance understanding of 3D spatial relationships and dynamic processes, making them valuable for studying complex cardiac conduction systems.

Understanding the relationship between ECG waves, particularly the P wave, and cardiac anatomy is crucial. The P wave represents atrial depolarization, starting in the sinoatrial node (SAN) and spreading across the atria. The location and activation patterns of the SAN significantly affect P wave morphology, which is shaped by various anatomical and tissue factors. Depolarization originates at the SAN and travels through key pathways such as the Crista Terminalis (CT), Bachmann's bundle (BB), and pectinate muscles (PM). These structures ensure coordinated atrial activation, which is reflected in the P wave on the ECG. Advances in mapping technologies have linked specific P wave shapes to distinct atrial conduction path-

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ways, aiding in the diagnosis of conduction abnormalities and offering insights into cardiovascular disease progression.

Analyzing P wave morphology is essential for diagnosing conduction disorders and identifying atrial abnormalities, such as enlargement or conduction delays. Factors such as SAN location, interatrial connections, and overall atrial anatomy influence the P waves form. Fibrotic changes in the interatrial bridges can delay conduction, increasing the risk of AF. Prolonged P wave duration, indicating delayed atrial conduction, is often associated with AF, although this can occur even in the absence of structural heart disease. Distinguishing between normal anatomical variability and pathological changes is critical for accurate diagnosis, especially in cases of atrial enlargement or electrolyte imbalances [**?**].

This study explores the relationship between atrial anatomy, P wave morphology, and activation sequences using advanced visualization techniques, including the Microsoft HoloLens 2. By integrating multi-modal data, this approach provides a comprehensive understanding of complex cardiac processes, enhancing both education and clinical applications in cardiac electrophysiology.

2. Methods

This study integrates multi-modal data to enhance the understanding of P wave genesis. By merging advanced visualization techniques with anatomical data, we aim to improve both learning and clinical interpretation of cardiac processes. The primary tools employed in this study include micro-CT (mCT) data of human atria, CineECG methodology, and an MR environment.

The micro-CT data were acquired and processed using methods outlined in previous studies [**?**]. For computational modeling and visualization, we used extracted a high-resolution triangulated mesh consisting of 498,121 nodes representing the atria [**?**].

For ECG analysis we used the CineECG tool, as traditional 12-lead ECG interpretation often overlooks anatomical relationships during wave propagation. CineECG addresses this by providing a 3D visualization of cardiac activation, mapping electrical processes onto the hearts geometry. It models electrical activity using a moving dipole vector computed through a series of vectorcardiograms (VCGs). The result is a compound trajectory tracking lead vector directions over time. This approach connects electrical activity with heart structures, offering real-time insights into cardiac depolarization [**?**].

We applied CineECG to analyze three different P wave morphologies: a healthy P wave, a negative P wave, and a P wave indicative of an interatrial block (IAB). These cases were selected from the PTB-XL ECG database [**?**] and are shown in Figure 1.

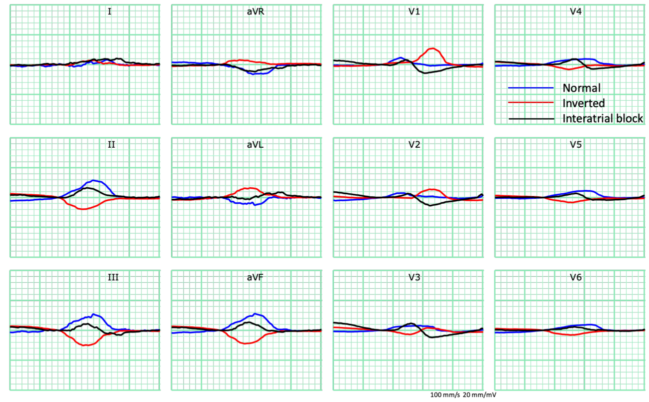

Figure 1: The 12-lead ECGs of the studied cases displayed together for each lead.

We combined mCT-based atrial anatomy with a generic torso model containing predefined ECG lead placements. This allowed us to compute the activation trajectories through the atrial geometry, starting with the SAN capture point. The earliest activation site (EAS) was identified based on its proximity to the trajectory onset, enabling us to model depolarization across the atria.

To refine the simulations, we calculated the fastest activation routes, incorporating regional conduction variations. For healthy and negative P waves, Bachmanns bundle (BB) and Crista Terminalis (CT) conduction velocities were set to 1.5 times the normal rate. In the IAB case, BB velocity was reduced to 0.5 m/s to mimic slower conduction. Finally, the simulations were optimized to match the recorded ECGs [**?**].

3. Results

The activation trajectories and corresponding activation times, overlaid on the atrial geometry, are shown in Figure 2. For the normal P wave, the activation begins near the SAN (segmented structure colored in yellow), as expected, and moves downward toward the left atrium (LA). Earlier depolarization is observed in the latero-anterior region of the right atrium (RA) and the lateral walls of the LA, areas known for faster conduction through the pectinate muscles and Bachmanns bundle (BB). The primary excitation pathway follows a downward, right-to-left direction, with the antero-lateral LA wall and inferior vena cava (IVC) being the last regions to activate.

In contrast, the inverted P wave displays an upward, left-to-right propagation pattern. The EAS is located in the lower part of the posterior wall, and the excitation spreads upward toward the LA and the upper RA.

For the case of the interatrial block, the activation pattern is significantly different. Instead of spreading to the

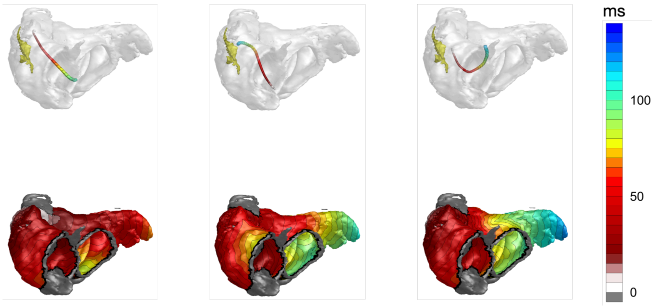

Figure 2: AP view of the atria with overlaid CineECG trajectories (upper row) and activation times (lower row) for normal, inverted and IAB-associated P waves (from left to right). This figure is adapted from [**?**]

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LA through Bachmanns bundle, the excitation leaves the paranodal area and moves inferiorly, likely activating the LA through interseptal connections. As expected, the left atrial appendage is the final region to depolarize.

The corresponding videos exported from the MR HoloLens software showcasing user interaction are to be found under the following links: normal, EAS from low sinus area, slow propagation through the Bachmann's bundle.

4. Discussion

The examples presented in this study demonstrate the benefits of combining multiple methodologies to overcome challenges in P wave analysis and improve teaching methods. Techniques such as mCT, CineECG, and MR-based tools like Microsoft HoloLens 2, while valuable on their own, cannot fully capture the intricate relationship between heart anatomy and its electrical function. However, integrating these methods provides a more comprehensive view, enhancing spatial understanding of the heart's structures and their interplay with electrical activity. This integration is especially important because the heart's electrical axis does not always align with its anatomical axis, often indicating underlying conduction issues [**?**]. Additionally, ECG-derived parameters can reveal sub-clinical markers of structural abnormalities in the heart. In patients with cardiomyopathy, where both anatomical and functional changes are prominent, detailed ECG interpretation can guide diagnosis and help to assess risk. Further factors complicating analysis include regional conduction disruptions, such as fibrosis, leading to low voltage electrograms and altered ECG signals [**?**].

Using mCT data allows for a detailed examination of critical anatomical structures involved in atrial electrical excitation, such as the SAN, CT, BB, and other conductive pathways. mCT delivers superior resolution compared to clinical CT scans, but it requires high radiation doses and long exposure times, limiting its use to post-mortem samples. To address this, we supplemented the anatomical data with ECG recordings from living individuals using the PTB-XL ECG database, which provided a range of normal and abnormal cases, including healthy P waves, inverted P waves, and interatrial blocks. Even though post-marted anatomy features thicker cardiac walls compared to a living heart, the level of conduction bundles delineation remains unparalleled.

CineECG, which estimates cardiac excitation patterns based on anatomical relationships between the heart, torso, and ECG leads, was used to merge the atrial anatomy into a generic body model. This approach is valuable both clinically and educationally, as it overlays the electrical excitation pattern onto the anatomical model, identifying areas of slow or blocked conduction and visualizing breakthrough points in the right and left atria. These visualizations make ECG interpretation and diagnosis more intuitive. The addition of HoloLens 2 technology further enhances the experience by offering an immersive environment, helping students and practitioners better understand the relationship between heart anatomy and electrical activity. Furthermore, MR environments foster greater engagement and collaboration, making them an effective tool in medical education [**?**].

In research, this combined approach could be useful for studying how anatomical variations affect cardiac conduction. Different individuals may show distinct ECG excitation pathways, and analyzing these differences can provide insights into conduction disorders. By combining detailed mCT data with HoloLens technology and cardiac simulation tools like the openCARP platform [**?**], various pathological scenarios and ECG patterns can be simulated and visualized. This is especially useful for education, helping students understand how anatomical changes impact cardiac function.

In clinical practice, integrating patient-specific ECG data with a generic anatomical template could assist in planning interventions such as ablations. The detailed maps of heart structures and electrical activation patterns generated by this approach can guide clinicians in identifying abnormal pathways and regions that require intervention.

While mCT offers high-resolution anatomical data, its clinical use is currently limited due to radiation exposure concerns, restricting its application to post-mortem studies. Therefore, the combination of patient-specific ECG data with a template mCT model, or any other model of a satisfactory accuracy, is necessary for clinical applications. Nevertheless, this approach is highly effective for educational purposes, providing a platform that merges anatomical and electrophysiological data in an accessible and user-friendly format.

CineECG offers a novel perspective on cardiac excitation, assisting students and clinicians with ECG interpretation. However, it does not deliver the same level of detail as invasive mapping techniques. Despite this limitation, CineECG provides valuable spatial information related to atrial conduction [**?**]. The use of HoloLens technology also presents some challenges. The high cost of both hardware and software may limit its adoption, especially in low-income settings. This could exacerbate existing inequalities in medical education. Additionally, using HoloLens effectively requires a basic understanding of cardiac imaging and electrophysiology, and the systems complexity in terms of configuration and maintenance could hinder its use.

5. Conclusions

In summary, the integration of high-quality imaging data with ECG analysis provides a powerful approach for enhancing our understanding of atrial electrophysiology. This methodology has significant potential in both medical education and clinical applications, particularly in diagnosing and treating cardiac conditions. The cases presented in this study will be made publicly available in a HoloLens-compatible format, aiming to raise awareness and support the development of educational platforms that combine multi-modal data for advanced learning and research.

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