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PROSPECTS OF CONTEMPORARY ANATOMOPHYSIOLOGICAL CONCEPTS OF THE HEART

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Abstract

This article examines contemporary anatomophysiological concepts of the heart that substantially expand the classical model of its structure and function. It is shown that emerging data on the deep Purkinje fiber network, the intrinsic cardiac nervous system, myocardial microarchitecture, and the characteristics of intracardiac blood flow broaden our understanding of the mechanisms underlying cardiac activity and the pathogenesis of cardiovascular diseases. Particular attention is given to 4D flow visualization techniques, diffusion tensor mapping, high-resolution ultrasound imaging, and the development of three-dimensional anatomical atlases. The authors conclude that the integration of these approaches opens new opportunities for more accurate diagnosis, personalized treatment planning, and the advancement of cardiology practice.

Keywords

heart, cardiac anatomy, cardiac physiology, intracardiac blood flow, Purkinje fibers, intrinsic cardiac nervous system, diffusion tensor mapping, digital heart twin

Relevance

Cardiovascular diseases (CVDs) remain the leading cause of death worldwide, claiming approximately 18 million lives annually [1]. Further progress in the diagnosis and treatment of CVDs requires a deeper understanding of the anatomical and physiological foundations of the heart. Traditional descriptions of the heart as a hollow muscular organ with four chambers, a valvular apparatus, and a well-defined conduction system formed the basis of clinical concepts of pathology. However, modern imaging modalities and molecular biology have revealed previously unrecognized features: for example, the discovery of the vortical nature of intracardiac blood flow and the complex “intrinsic cardiac nervous system” demonstrates that conventional models require re-evaluation [2], [3]. These new insights promise to deepen our understanding of cardiac pathophysiology and lead to more precise diagnostic and therapeutic methods.

Introduction

Classical anatomy describes the heart as a four-chambered organ consisting of two atria and two ventricles separated by a septum, enclosed by three layers (the endocardium, myocardium, and epicardium), and equipped with a valvular apparatus and coronary vessels. The principal physiological processes are well established: the contraction phase (systole) and relaxation phase (diastole), impulse conduction from the sinoatrial node through the atrioventricular node to the ventricles, and regulation of blood flow. The clinical relevance of these concepts is evident: for example, ventricular hypertrophy in hypertension alters cardiac geometry, which is reflected in the electrocardiogram and in circulatory function, whereas coronary artery damage leads to myocardial infarction. However, many aspects remain insufficiently explored. Until recently, the internal micro- and macrostructure of the heart was studied with limited precision. Only now have technologies such as magnetic resonance diffusion tensor imaging (DTI) made it possible to visualize how myocardial fiber orientation influences function: in patients with dilated cardiomyopathy, changes in the fiber helix angle and impaired dynamic redistribution during contraction have been demonstrated [4]. Such findings show that the myocardial microarchitecture is closely linked to the development of cardiovascular diseases, a relationship that was not previously adequately considered in routine practice.

Materials and Methods

This study was conducted as an analytical review of the contemporary scientific literature devoted to cardiac anatomy, physiology, and imaging. The material included publications reporting research on the intracardiac conduction system, the neural organization of the heart, diffusion tensor magnetic resonance imaging, 4D flow assessment, high-frequency ultrasound tracking, and the development of three-dimensional cardiac atlases. A comparative analysis was performed between classical anatomophysiological concepts and recent experimental and clinical data, with emphasis on their diagnostic and therapeutic significance.

Objective of the Study

To examine and identify the future prospects of contemporary anatomophysiological concepts of the heart for the further development of cardiology.

Results

It was established that modern imaging techniques make it possible to identify previously underestimated features of cardiac structure, including the deep extension of Purkinje fibers into the myocardium, the presence of a distinct intrinsic cardiac neural network, and the complex architecture of myocardial fibers. It was also shown that intraventricular blood flow has a pronounced vortical character, which influences filling efficiency and the pumping function of the heart. The use of diffusion tensor imaging and 3D atlases enables a more accurate study of myocardial microstructure, while the combination of imaging with electrophysiological and computational models provides the foundation for digital heart twins.

Discussion

The findings indicate that the traditional view of the heart as a relatively simple pumping system requires substantial revision. The discovery of hidden elements of the conduction system, intrinsic cardiac neurons, and the complex spatial organization of blood flow helps explain a number of clinical phenomena, including arrhythmias, impaired contractile mechanics, and the limited effectiveness of certain therapeutic interventions. The most promising directions appear to be the implementation of 4D flow tomography, wider use of high-precision echocardiography, application of detailed three-dimensional mapping, and the creation of personalized digital heart models. Collectively, these advances may improve diagnostic accuracy and optimize treatment selection in patients with cardiovascular disease.

Main Section

New findings regarding the anatomy of the heart significantly expand upon classical concepts. One of the key discoveries concerns the cardiac conduction system. For a long time, it was assumed that Purkinje fibers were located primarily in the subendocardium. However, a study by B. Behfar’s group (Mayo Clinic, 2025) showed that the intramural network of Purkinje fibers extends deep into the myocardial wall, accounting for more than 60% of all Purkinje fibers [5]. This discovery overturns the understanding of the three-dimensional structure of the conduction system and challenges the traditional model of the “superficial” location of pacemakers. The authors suggest that it is precisely this hidden network that may be the cause of arrhythmia recurrences and the ineffectiveness of certain types of ablation or resynchronization therapy [5].

In addition, a whole complex of intracardiac neurons (“the heart’s mini-brain”) has been identified. Previously, it was believed that the heart rhythm was controlled solely by the autonomic nervous system from outside the heart. Recent studies (Karolinska Institutet, 2024) using single-cell sequencing and electrophysiology in zebrafish models have shown that the heart contains its own complex network of neurons with various functions, including pacemaker properties [3]. These neurons not only transmit signals but can also generate a rhythm themselves. It has been established that disruptions in this intracardiac system can lead to arrhythmias, and the study of the “heart’s brain” opens up new possibilities for treatment, such as targeted therapy for refractory arrhythmias [3].

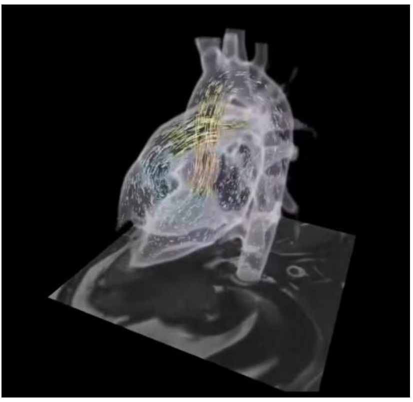
The structure of the myocardium is becoming clearer thanks to advanced methods. Diffusion tensor MRI (DTI-MRI) allows for the mapping of cardiac fiber orientation in vivo. Such studies reveal how the orderliness of the fiber bundles is disrupted in various pathologies (infarction, hypertrophy, dilation) [4]. For example, in dilated cardiomyopathy, the helix angle of the fibers is steeper, and the fibers’ ability to change orientation during contraction is reduced [4]. Understanding these changes is important for explaining mechanical abnormalities in heart failure and developing new therapies focused on myocardial remodeling.

Physiological processes in the heart have also proven to be more complex than previously thought. For instance, using 4D blood flow tomography, it has been shown that stable vortex and spiral blood flows form within the ventricles [2]. These flows help conserve energy during diastole and create favorable conditions for chamber filling. High-frame-rate echocardiographic methods (blood speckle tracking) allow these flows to be visualized in real time [6]. For example, P. Nirness and colleagues found that such analysis can provide new insights into hemodynamics in children and fetuses and proposed incorporating it into clinical studies of heart diseases [6]. Understanding vortex flows is important for diagnosis: abnormalities in these flows are found in cardiomyopathies and valvular defects, and the appearance of extravasal vortices may be an early sign of aortic valve stenosis or an aneurysm [2].

Finally, new three-dimensional imaging of the heart has yielded unique anatomical atlases. Synchrotron computed tomography (HiP-CT) has made it possible to scan entire human hearts with a resolution of up to 20 μm, creating a “Google Earth for the heart” [7]. The result is a 3D atlas of healthy and diseased hearts, where the microstructure of tissues and blood vessels is visible in minute detail [7]. In such atlases, for example, the density of muscle fibers and the condition of blood vessels in a diseased heart with coronary artery disease are clearly distinguishable. Scientists note that these resources provide insight into the complex connections within the heart and are particularly helpful in clarifying the structure of the conduction system [7]. In the future, this will enable the modeling of heart diseases at the molecular level and the development of targeted treatment methods that account for individual anatomical features.

Modern Methods of Detection and Reinterpretation

The implementation of these discoveries has been made possible by new diagnostic techniques. 4D flow MRI allows for the quantitative analysis of blood flow velocity and direction within the heart and blood vessels, identifying spiral, retrograde, and vortex components (see *Fig. 1; a, b, c, e, f*) [2]. High-density ultrasound technologies (vector flow mapping, blood speckle tracking), combining color Doppler and tracking, complement this arsenal by visualizing local velocity vectors and energy dissipation of blood within the heart chambers. These methods are already used in clinical practice: for example, vector flow mapping (VFM) helps assess hemodynamic changes in valvular heart disease and heart failure, while blood speckle tracking is applicable even in fetuses and children [6]. Diffusion MRI (DTI) is actively used for mapping myocardial fibers. This method provides a continuous representation of the structure of the heart's muscle network. In clinical studies, DTI allows for the identification of areas of fibrosis and fiber dyssynchrony, which is valuable in cardiomyopathies and ischemia [4]. Neuromarker approaches are also being developed: in a study by Behfar et al., a new biomarker, MYL4, was used to accurately visualize Purkinje cells [5]. These molecular markers, combined with optical and immunological imaging, reveal previously inaccessible "secrets" of the conduction system



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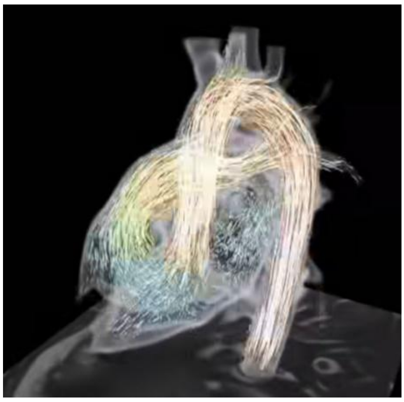

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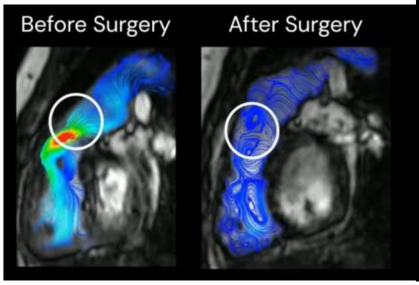

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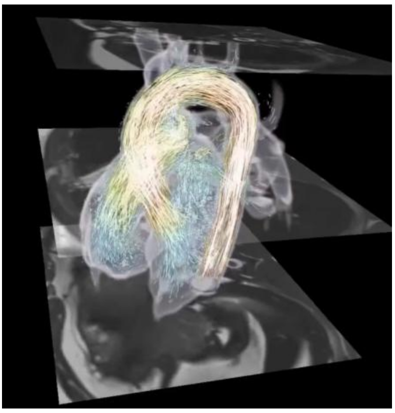

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Figure 1. *This figure shows computer-simulated illustrations of 4D flow MRI in the heart. Figures a, b, c, e,* and *f* depict visualizations of vortex blood flows in the heart chambers obtained using 4D flow MRI. The spatio-temporal characteristics of blood flow are depicted, including the identification of vortex formation zones, flow directions, and their interaction with anatomical structures. *Figure d* presents a comparative visualization of intracardiac hemodynamics *before* and *after* surgical correction.Modern computer models and "digital twins" of the heart link imaging data with electrophysiology. Based on UK Biobank data, simplified 3D models of the heart were created and correlated with ECG recordings for 39,000 individuals [8]. This demonstrated that natural variability in heart orientation (e.g., due to age, sex, BMI, or hypertension) significantly influences electrocardiographic signals [8]. Such integration of images and ECG data facilitates personalized diagnosis of CVD and more accurate disease prediction.

Finally, high-performance computing and large datasets help analyze 3D heart atlases [7]. Large volumes of HiP-CT images are synchronized with clinical cases, providing a unique "library" of normal and pathological anatomy. These resources are already being used to train surgical skills and plan interventions; for example, the heart atlas will serve as the basis for creating realistic models in the training of arrhythmia ablation [7].

Recommendations for Implementation

Widespread use of 4D flow MRI: we recommend developing clinical protocols for 4D flow tomography in patients with suspected diastolic dysfunction, congenital defects, or valvular diseases [2]. This will allow for the detection of previously hidden hemodynamic abnormalities and the assessment of treatment efficacy in the early stages (see *Fig. 1; d*). For example, as shown in Figure d, a distinct zone of accelerated blood flow (red-yellow spectrum) is identified, corresponding to a local increase in velocity and the formation of turbulent or pseudo-turbulent flows. In the highlighted area, a disorganized vortex structure is visualized with signs of energy losses and uneven velocity distribution, which may reflect hemodynamically significant obstruction or geometric deformation of the lumen. Following surgical interventions, a significant decrease in peak blood flow velocity (predominance of the blue spectrum) is observed, as well as the restoration of a more laminar and organized flow pattern. Vortical structures become less pronounced and acquire a physiologically directed configuration. A reduction in turbulence and a more uniform distribution of the velocity vector field are observed. The data obtained indicate an improvement in intracardiac hemodynamics following surgical correction, manifested by a reduction in flow energy losses, normalization of vortex formation, and a potential decrease in myocardial workload.

Vector mapping in routine echocardiography: implement VCM and high-frequency blood speckle tracking in echocardiography, particularly in pediatric cardiology and in valvular pathology [6]. Such techniques are already commercially available in modern devices and help to quantitatively assess energy expenditure during inefficient flow.

Electrophysiological 3D mapping: expand the use of mapping systems (e.g., EnSite/CARTO or equivalents) taking into account new anatomical data. The knowledge gained about the deep network of Purkinje fibers and cardiac nerve cells can be applied in ablation planning: for example, to search for sources of arrhythmias not only in the endocardium but also within the muscle tissue [3], [5]. Some expert groups are already using electrophysiological mapping with Purkinje markers (MYL4) for precise navigation [5].

Personalized modeling: develop digital heart twins for clinical use. CT/MRI and ECG data from each patient can be used to create 3D models on which treatment strategies are tested (e.g., selection of sites for radiofrequency ablation or optimal positions for pacemaker leads) [8]. This will allow for consideration of individual variations in anatomy and the heart's electrical axis, increasing the accuracy of the procedure.

Interdisciplinary atlases and training: use accumulated 3D atlases (HiP-CT) and experimental data to train physicians and develop educational simulators [7]. In particular, the practical implementation of a "heart atlas" could include the creation of printed models, virtual simulations, and pre-designed surgical scenarios. Already today, these atlases are used in research centers as a basis for improving arrhythmia ablation techniques and in cardiac surgery.

Many of the proposed approaches have already been tested. For example, 4D flow studies are actively used in cardiology clinics at major research centers and are gradually being incorporated into examination protocols for complex patients. Vector blood mapping has proven effective in the non-invasive assessment of heart and vascular function. Three-dimensional electrocardiography and anatomical mapping systems are widely used in electrophysiology, and the application of "digital twins" is undergoing clinical trials. The use of these methods is already demonstrating improved diagnostic accuracy and a positive impact on treatment outcomes.

Conclusion

Thus, modern research has significantly expanded our understanding of the structure and function of the heart. The discovery of vortex blood flows, detailed mapping of muscle fiber distribution, and the identification of the heart's hidden conduction and nerve networks demonstrate that traditional models involved significant oversimplifications [2], [5]. This new knowledge not only enriches fundamental research on the heart but also has direct clinical implications. For example, a three-dimensional atlas of the heart promises to improve the treatment of arrhythmias by more accurately accounting for electrical conduction, and an understanding of the complex Purkinje network will open the way for improving ablation and cardiospacing methods [5], [7]. The introduction of modern imaging and analysis methods (4D flow MRI, CCV, DTC, digital twins, etc.) will allow us to rethink many aspects of the pathophysiology of CVD and improve the effectiveness of therapy, which will ultimately lead to a reduction in the burden of heart disease.

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