Digital 3D Heart Modelling for Cardiac Structure and Abnormality Analysis: A Survey

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DOI: https://doi.org/10.51584/IJRIAS.2026.11110027

Received: 31 October 2026; Accepted: 05 November 2026; Published: 23 November 2026

ABSTRACT

As it is the leading cause of deaths around the world, cardio-vascular disease (CVD) necessitates precise diagnostic information about the anatomy of the cardiovascular system [2], [8], [20]. Cardiac Magnetic Resonance Imaging (MRI) is a prominent non-invasive tool thanks to its high soft-tissue contrast, rendering it ideal for non-invasively characterization and analysis of the cardiovascular structures [1], [2], [9]. Yet, current conventional 2D analyses yield a somewhat restricted understanding of 3D cardiac anatomy and may result in an insufficient characterization, limited management, and personalization of treatment of various CVDs [9], [15], [20].

With breakthroughs of Artificial Intelligence (AI) in recent years, several approaches using various Deep Learning (DL) techniques (such as convolution-al neural networks, transformers, attention mechanisms, generative networks, etc.) have demon-strated considerable success in the task of automated MRI car-diac image segmentation, patient-specific 3D cardiac modeling, as well as in characterizing pathologies of cardiac structures [3], [5], [13], [16]–[18].

The recently emergence of the neural implicit representation approach, diffusion-based generative models and AI based computational fluid and solid modeling are promising alternative approaches for the creation of highly accurate 3D digital heart models [1], [4], [6]–[8], [15]. In this survey paper, we briefly introduce the state-of-the-art and the merits/demerits of state-of-the-art AI techniques for: (i) cardiovascular image analysis;

(ii) automated digital 3D cardiac modeling; and (iii) the characterization of cardiac pathologies. We further discuss unresolved questions and put forward some directions for future work on AI technologies to develop intelligent and explainable solutions that contribute to accurate clinical cardiovascular diagnosis.

Index Terms—Artificial Intelligence, Cardiac Abnormality Analysis, Cardiac Magnetic Resonance Imaging (MRI), Clinical Decision Support, Deep Learning, Digital Heart Modeling, **Medical Image Segmentation, Three-Dimensional Heart Reconstruction, U-Net, Vision Transformer.**

INTRODUCTION

Background Since cardiovascular diseases (CVD s) have remained a leading global cause of death, it is important to develop robust diagnostic methods and to treat patients suffering from CVD s [2], [8], [20]. For cardiac visualization (e.g., Cardiac Magnetic Resonance Imaging (MRI), Com-puted Tomography (CT) scan and echo cardiography) that are beneficial for diagnoses, it is crucial that the generated imaging is informative and precise. Cardiac MRI has been proven to outperform other imaging modalities because of its ability to differentiate tissues by their soft-tissue contrast, to render images non-invasively with remarkable spatial and time resolution, and to effectively demonstrate the anatomy and physiology of the heart in both space and time [1], [2], [9].

Unfortunately, the traditional 2D-based segmentation and analysis based on several 2D slices may not adequately re-flect complicated three-dimensional (3D) spatial relationships among various cardiac chambers, leading to poor cardiac diagnosis and planning [9], [15], [20].

Recently, impressive advances in artificial intelligence (AI) and deep learning (DL) techniques [2], [3], [13], [18] have given promise for automated analysis and cardiac image segmentation. For instance, many neural network architectures, such as U-Net [3], [5], [13], [16], V-Net [2], [18], 3D U-

Net, UNet++ [3], transformer-based models [18] and attention mechanisms [17], could achieve high performance with even less annotated data or imbalanced data distributions. Detailed segmentation of the cardiac anatomy on 3D cardiac images is a critical first step that forms a foundation for detailed 3D heart modeling with enhanced cardiac function estimation, for identifying cardiac diseases and treatment personalization [4], [6], [7], [10]. In recent years, digital 3D heart modeling techniques have flourished in the area of cardiac disease diagnosis by virtue of Neural Implicit Representations [1], [4], [11], generative diffusion models [6], [7] and AI assisted modeling algorithms [8].

However, most current methods still suffer from dependence on appropriately large annotated data [4], [7], [8], high costs of computational and training time [2], [7], [10], [13], limitations in generalization ability [2], [8], [10], [13], [18], lack of a uniform framework for segmentation and digital 3D heart modeling and clinical application, and the difficulties in automated cardiac pathology detection [7], [8], [20].

Therefore, in this review survey, we offer a critical appraisal of the latest developments in AI-driven Cardiac MRI seg-mentation, digital 3D heart modeling and automated cardiac analysis. Various AI-based techniques for these problems are categorized and compared, extant research challenges and future directions are identified.

Deep Learning Based Cardiac MRI Segmentation

Cardiological MRI Accurate segmentation of cardiovascular MR scans plays a critical part in three dimensional recon-struction of the heart, quantitative cardiological analysis and disease diagnosis. Manual annotation is very tiresome and costly, and it often produces varied results caused by inter-observer variations. For this sake, various automatic deep learning (DL)-based approaches have been developed[3, 12, 18].

In particular, the pioneer and widely acclaimed deep learn-ing model U-Net is primarily formed of the two network path-ways in the encoder-decoder network and the skip connections between feature maps at various levels, which successfully promote the automated segmentation of cardiac organs such as LV, RV and myocardial wall[13, 16, 17].

The variations of it including V-net[22], 3D U-net[1] and UNet++[9] were introduced to incorporate feature hierarchy to the information of spatial localization while exploiting both long range dependency within volumes and the details of features local. There has been immense effort made in recent years using various other approaches, including various atten-tion mechanisms, deep learning techniques with transformers and semi-supervised learning methods with reduced number of labels[3, 5]. The state-of-art, such as Multi View Semi-Supervised Attention Networks[3], Semiotic[5] etc. Perform well on segmentation with small scale labeled data.

Yet most recent approaches have serious shortcomings like requiring sufficient volume of annotated images and computation resources as well as poor flexibility for varied MRI datasets or diverse health statuses[1, 3, 5, 12].

Three-Dimensional Heart Reconstruction

Techniques

Three-Dimensional Heart Reconstruction Techniques Con-verting Cardiac Images to Patient Specific Models The 3D reconstruction technology aims to translate patient-specific segmented 2D imaging with corresponding labels(masks) to patient-specific cardiac digital models to achieve greater in-sight for the anatomical structure , diagnosis and assessment, interventions planning, quantitative analysis of heart [8]–[10], [15], [19] because compared with 2D analysis of imaging data

, 3D visualization offers a more natural and enhanced perspective of 3D structures. Classical Methods Patient specific heart 3D geometric reconstruction can be performed classically by using image process and surface reconstruction and meshing based on MRI/CT imaging segmentation's [9], [10], [19]Al-though this technique allows for improvement of visualisation of the cardiac anatomy , it suffers greatly from the accuracy of the cardiac image segmentation process and requires extensive user interaction. Modern Deep Learning Methods In recent years , deep learning approaches has achieved remarkable progress on patient-specific heart reconstruction : NIHCRE construct Anatomically Consistent 3D Patient-Specific heart models from Few Shot segmentation's of cardiac MRI via an implicitly parameterization shape using Neural implicit Representations [1], [4], mesh latent diffusion models and personalized time-resolved mesh generators for improved shape and time-resolved prediction in modeling cardiac shape during heart cycles [6], [7] Recent efforts havegenerate Highly Accurate 3D Shapes anded Time-Resolved Models for Cardio Vascular Motion[6, 7]Applications The 3D models can be utilized for the Diagnosis of structural heart disease [8], [15] , numerical/computational simulations [11], [14] , 3D printing of cardiac-anatomies[14, 15] .

For Surgical Intervention planning and guidance[8, 11, 14, 15], Digital Twin for Cardiology[11] and personalized cardiovascularand Personalized CVD s diagnosis and treatment[14].

Challenges High compute cost, a shortage of annotated dat>, andcross-dataset robustness due to protocol variations are three challenges that need to overcome in clinical adoption [1], [4], [6], [10].

AI-Based Cardiac Abnormality Analysis

The field of Cardiovascular Abnormalities Detection Clas-sification and Quantification with medical imaging data set have taken enormous strides with AI in recent years. With less than few decades ago, the diagnoses have been done based on expert Cardiologist by visually examining an MRI or CT heart scans, which is a tedious and costly process. In addition, manual interpretation is often different for individual experts in various occasions [2, 8, 20].

The AI based cardiovascular diagnostic approaches demon-strate capabilities of extracting discriminate spatial and func-tional information in relation to human heart disease, to the point that they can perform better than cardiologists in some cases,.

There has been many deep-based deep learning-based frameworks, aiming to achieve end-to-end automate process of the cardiac abnormality Detection Classification Segmentation and Quantification of data from human heart image. The MRI-based Heart Disease Diagnosis method from deep CNN along with contrast limited adaptive histogram equalization's (CLAHE), feature fusion and Atom Search Optimization (ASO) achieve efficient and accurate cardiovascular diagnosis of disease from MRI Images [2]. Special attention on automatic segmentation process the SemCoTr and Multi View Semi-Supervised Attention Networks models perform well on predicting exactness based on the shape variation of the heart chambers and motion of cardiac walls[3,5]. Aside from Segmentation of the cardiac region.

Numerous research have achieved 3D heart shape reconstruction such as from neural implicit heart coordinates, Mesh Latent Diffusion Models, personalized Time-Resolved 3D Mesh Models to quantitatively estimating the heart morphology and function to support a variety of downstream tasks: the ventricular shape, wall thickness size and wall motion for instance[4, 6, 7].

This patient specific heart models allow for the detailed anatomical analysis in terms of complex structural abnormalities like Congenital Heart Diseases, remodeled Ventricles, etc. The deformation of ventricle walls as well as MRI, can be efficiently detected as well. Besides of the straightforward cardiac cardiovascular assessment, 3-dimensional digital representations the with the usage of Al and deep learning provide a diverse usage range in the practice such as assist Surgeons planning the most intricate operation and understand each patient's own body [8,11,14,15], patient Simulation and training or individualized treatment.

Clinical physicians have the ability to produce a 3D Printed heart to study a detailed operation of a given patient and also comprehend patient anatomy and interact with them in an efficient way with all the aid from this field

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume XI Issue XI November 2026

and the technology itself of 3D Printing. Even the field has progress quickly on automating cardiovascular diagnosis through machine learning, many issues like insufficiency of training data, sensitivity to the changes in imaging scanner and technique and even anatomically individual differences in people remain[1,3,5]. The integration of several different AI models such as diagnosis, automatic segmentation, and image reconstruction for automatic estimation and quantifiable cardiac parameters, along with visually explicable heart models remains a funda-mental challenge, which have resulted in limiting applications in diverse clinical context

DISCUSSION

Artificial Intelligence (AI) and Deep Learning (DL) have made impressive strides in cardiac imaging applications by improving accuracy and autonomy in cardiac MRI segmentation, 3D reconstruction of heart anatomy, and abnormality detection. CNN-based structures like U-Net, V-Net and UNet++ lead segmentation accuracy by exploiting both local and global image information while transformer-augmented and semi-supervised methods excels in scenarios with sparse annotations [3], [5], [13], [16]–[18], greatly reducing the reliance on manual annotation. With numerous breakthroughs made in neural implicit representations (NIR),diffusion-based genera-tive models and deep learning-based reconstruction frame-work, patient-specific 3D reconstruction of the heart is capable of efficiently and accurately reconstructing an individualized complex 3D anatomical structure from a sparse collection of MRI slice information, whilst maintaining anatomical continuity and geometric continuity [1], [4], [6], [7], [10]. Their adoption in computational models and 3D printing extends their functionality to assist surgeons with surgical planning, anatomical structure analysis, and personalized medicine.

However, there exist key limitations and challenges for their broad clinical translation: MOST deep-learning models requiring a significant volume of labeled images and high computational resources to yield satisfactory results on their own. Varied MRI protocols, common artifacts, and the individual differences in patient geometry are significant impediments to widening sustainability across varied clinics [1], [3], [5]. Thus far only limited number of studies have integrated personalized 3D heart reconstruction, automated segmentation, abnormality detection and the calculation of various quantitative cardiac measurements in to an unified architecture to draw immediate conclusions for a rapid analysis process.

Future research should focus on Developing lightweight, low-overhead DL models; building robust and adaptive frame-works to overcome data heterogenetic challenges; fusing information from diverse retrieval modes; integrating explainability tools to gain interpretation capabilities; and developing digital twins and personalized tools as cornerstones to next generation cardiovascular imaging infrastructure and digital health systems.

TABLE I: Comparative Analysis of Existing Studies

Sl.	Paper Title (Year)	Methodology	Advantages	Limitations
1	Fighting MRI Anisotropy: Learning Multiple Cardiac Shapes from a Single Implicit Neural Representation (2026)	Implicit neural representation for cardiac shape reconstruction	Improves cardiac shape recovery from anisotropic MRI	Requires large annotated datasets for training
2	MRI-Based Heart Disease Diagnosis: An Automated IBNet9X-DenseNet8X Framework for Optimal Feature Fusion and Classification (2026)	DenseNet with feature fusion for disease classification	High diagnostic accuracy for cardiovascular disease	Computationally intensive training
3	Efficient Cardiac MRI Multi-Structure Segmentation for Cardiovascular Assessment with Limited Annotation (2026)	Transformer-assisted SemiCoTr segmentation	Accurate segmentation using limited annotations	Limited cross-dataset generalization
4	Neural Implicit Heart Coordinates: 3D Cardiac Shape Reconstruction from Sparse Segmentation's (2025)	Neural implicit representation for 3D reconstruction	Produces accurate patient-specific heart models	Sensitive to segmentation quality

5	A Multi-View Semi-Supervised Attention Network for 3D Cardiac Image Segmentation (2025)	Attention-guided semi-supervised segmentation	Improves segmentation with fewer labeled samples	Performance depends on label quality
6	3D Cardiac Anatomy Generation Using Mesh Latent Diffusion Models (2025)	Mesh latent diffusion-based generative modeling	Generates realistic three-dimensional cardiac anatomy	Requires high computational resources
7	A Personalized Time-Resolved 3D Mesh Generative Model for Unveiling Normal Heart Dynamics (2025)	Generative temporal mesh reconstruction	Captures dynamic cardiac motion accurately	Requires temporal MRI datasets
8	3D Printing, Computational Modeling, and Artificial Intelligence for Structural Heart Disease (2020)	AI-assisted computational modeling with 3D printing	Enhances structural heart disease assessment	Limited large-scale clinical validation
9	Cardiovascular Medical Image Analysis Based on 3D Vision: A Comprehensive Survey (2024)	Survey of AI-based three-dimensional vision techniques	Comprehensive review of recent methods	No experimental implementation
10	A Completely Automated Pipeline for 3D Reconstruction of Human Heart from 2D Cine Magnetic Resonance Slices (2021)	End-to-end deep learning reconstruction pipeline	Fully automated heart reconstruction	Evaluated on limited datasets

CONCLUSION

Cardiovascular diseases persist as one of the leading cause of mortality on a global scale, accentuating the necessity for reliable assessment of the heart structure for the planning of effective interventions. This survey evaluated up-to-date progress in the realm of DL-based cardiac MRI segmentation, three-dimensional heart reconstruction and AI assistance on cardiac abnormalities detection. We identified multiple top-performing approaches such as CNN-based architectures, transformer-aid segmentation methods, Neural Implicit Representations, diffusion-based generative models, as well as computational modeling techniques, which provide an improved automate, precise and dependable performance regarding the patient specific heart characterization.

Despite major leaps in the field, major pitfalls still challenge further research: the availability of labeled datasets, the computational cost of those methods, their generalization within multiple domains and the absence of common integrated frameworks which may embrace segmentation, rendering and automated identification of cardiovascular dysfunctions.

Facing up to such challenges is fundamental in the path for better deployment on a clinical level of AI-based imaging for the cardiovascular assessment and medical application on the near future, whereas the following researches shall expand and investigate Explainable AI approaches, Multi model Image Registration, Digital Twins technologies, and clinical diagnosis assisted system that can bring precise explanation and personally driven diagnostics on daily practice by leveraging advancements of AI with biomedical imaging including three-dimensional imaging on patient diagnosis for the benefit of patients.

ACKNOWLEDGMENT

The authors express their sincere gratitude to the Department of Information Science and Engineering, Global Academy of Technology, Bengaluru, for providing the necessary facilities to carry out this survey. The authors would also like to express their heartfelt thanks to their guide, Prof. Hemanth Chandra N, for his continuous guidance, valuable suggestions, and constant encouragement throughout this work.

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