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CASE REPORT

Dynamic 3D Simulation Modeling for Surgical Management of Giant Congenital Left Ventricular Diverticulum: A Case Report

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ABSTRACT: Background: Congenital left ventricular diverticulum is an uncommon cardiac malformation that may present with chest pain, ventricular arrhythmia, thromboembolism, or rupture risk depending on lesion morphology and wall composition. **Case description:** We report an adolescent male with chest pain and frequent premature ventricular complexes who was found to have a giant apical left ventricular diverticulum with marked wall thinning and regional hypokinesia. Multimodality imaging, including transthoracic echocardiography, computed tomography, cardiac magnetic resonance, and myocardial perfusion/metabolic assessment, supported the diagnosis of a fibrous diverticulum and helped exclude ischemic myocardial injury. To refine operative planning, patient-specific dynamic three-dimensional (3D) simulation modeling was performed preoperatively to delineate the diverticular neck, estimate the residual ventricular cavity, and define the spatial relationship between the lesion and adjacent coronary branches. Surgical repair was completed under cardiopulmonary bypass by intracavitary exclusion of the neck with a bovine pericardial patch, followed by resection of the diverticular sac and reinforced sandwich closure of the residual ventricular wall. Pathology confirmed a fibrous diverticulum. The postoperative course was uneventful, and follow-up demonstrated relief of symptoms without documented recurrent arrhythmia. **Conclusion:** This case highlights the adjunctive value of dynamic 3D simulation modeling in complex ventricular reconstructive surgery by improving spatial understanding, facilitating individualized operative planning, and supporting preservation of residual ventricular function.

KEYWORDS: Left ventricular diverticulum; 3D simulation modeling; surgical management

1 Introduction

Congenital ventricular diverticulum is a relatively rare clinical disease. While most cases are incidentally detected during physical examinations, some patients may present with arrhythmias, embolic events of unknown origin, or chest pain as initial symptoms. This condition can occur in either cardiac ventricle, with a predilection for the left ventricle. Pathologically, congenital ventricular diverticula are classified into

fibrous and muscular types. The primary management strategy involves antiarrhythmic and anticoagulation therapy. Surgical resection may be considered for selected high-risk patients with a significant risk of rupture. Advances in digital imaging technology have enabled the application of dynamic three-dimensional (3D) simulation modeling, which facilitates preoperative planning by delineating surgical details. This approach can reduce intraoperative exploration time, minimize the risk of injuring critical structures, and ultimately enhance procedural safety and therapeutic efficacy. Our institution has begun to employ this technique in selected complex cases. The overall clinical prognosis for congenital left ventricular diverticulum is generally favorable. However, some patients may experience residual ventricular dysfunction or persistent arrhythmias, necessitating long-term pharmacologic management.

With the advancement of digital medicine and the clinical application of 3D printing technology, 3D modeling and its derivative technologies are being progressively integrated into clinical practice. These technologies offer complementary strengths. Traditional 3D-printed models excel at visualizing the three-dimensional relationships and spatial anatomy of extracardiac structures, such as vessels, with high fidelity. However, their static nature limits the provision of dynamic, multi-planar views, resulting in less comprehensive and intuitive visualization of crucial intracardiac structural relationships. Dynamic 3D simulation modeling not only matches the intuitive, stereoscopic display of traditional models for extracardiac anatomy but also allows the operator to set various viewing angles. Similar to multi-planar computed tomography (CT) reconstruction, it reveals spatial relationships across different sections, providing surgeons with enhanced spatial perception. This capability facilitates a multi-perspective understanding of the spatial architecture within the heart. In selected cases, when combined with real-time annotation features, it enables more meticulous and thorough surgical planning. For complex cases, augmented reality (AR) and virtual reality (VR) technologies can be employed to simulate intracardiac exploration, offering a more precise anatomical foundation for multi-dimensional cardiac assessment. Utilizing dynamic 3D simulation for rational preoperative planning can improve surgical efficiency and, consequently, enhance procedural safety [1]. In this specific case, we utilized dynamic 3D simulation modeling preoperatively to accurately delineate the location of the ventricular diverticulum. Its spatial relationship to adjacent major coronary arteries, and the position of the diverticular neck. It also allowed for a precise assessment of the residual ventricular cavity volume. This comprehensive preoperative planning has the potential to reduce both the intraoperative exploration time and the aortic cross-clamp time.

Furthermore, three-dimensional animation was used to simulate ventricular kinetics post-resection. Employing 3D-motion technology to visualize the differences in ventricular wall motion before and after the proposed resection, it provided valuable decision support for determining the optimal extent and location of tissue removal. This approach was instrumental in maximizing the preservation of residual ventricular function and ensuring the protection of vital coronary branches.

2 Case Presentation

The patient was an 18-year-old male adolescent who initially presented to a local hospital with a 4-day history of chest pain. Two days later, a routine electrocardiogram performed at the local hospital demonstrated sinus arrhythmia, occasional premature ventricular contractions, nonspecific intraventricular conduction delay, and ST–T abnormalities in multiple leads. Transthoracic echocardiography revealed segmental wall motion abnormalities, thinning of the apical ventricular wall with possible ventricular aneurysm formation, mild mitral regurgitation, and mild tricuspid regurgitation, while global left ventricular systolic and diastolic function remained essentially preserved. No specific treatment was administered, and the patient was subsequently referred to our institution for further evaluation and management. The study is

a single retrospective case report. Informed consent was obtained from the patient's legal guardians for the publication of this case and related images. Ethical approval was not required according to the institutional guidelines for single-case reporting. The CARE Checklist is attached as Supplementary Materials; informed consent forms are available upon request. The study was conducted in accordance with the Declaration of Helsinki.

An electrocardiogram performed at our institution on the day of admission showed sinus rhythm with intraventricular conduction delay and abnormal Q waves in leads II, III, aVF, and V4–V6. Holter monitoring demonstrated frequent premature ventricular complexes with occasional couplets, and transthoracic echocardiography suggested an apical outpouching with localized wall thinning. Four days after admission, Contrast-enhanced cardiac CT demonstrated an enlarged left ventricle and an apical sac-like protrusion measuring approximately 47 × 24 mm, and cardiac magnetic resonance confirmed a giant apical diverticulum (approximately 60 × 39 mm), severe left ventricular enlargement, regional wall thinning and hypokinesia, mildly reduced global left ventricular systolic function, and preserved right ventricular function (Fig. 1). Contrast-enhanced cardiac CT data were used to generate patient-specific three-dimensional (3D) models with the open-source software 3D Slicer, the software version used in this study is 3D Slicer 5.10.0, developed by the Surgical Planning Lab at Brigham and Women's Hospital, Harvard Medical School, in Boston, USA. Myocardial perfusion imaging performed one week after admission showed reduced perfusion in the apical and peri-apical segments with preserved coronary flow reserve, supporting a non-ischemic fibrotic lesion. Preoperative left ventricular ejection fraction was 57%, and the end-systolic volume was 63 mL. Preoperative cardiac enzyme profiles were within normal limits. The patient's past medical history includes a diagnosis of "short stature," for which he received growth hormone replacement therapy over three years. He was also diagnosed with "scoliosis" over one year ago and is currently undergoing orthotic management. One month prior to admission, he reported a self-limited episode of upper respiratory infection and diarrhea (details unspecified). There is no history of febrile exanthematous illnesses, blood transfusions, trauma, surgical procedures, or toxic exposures.

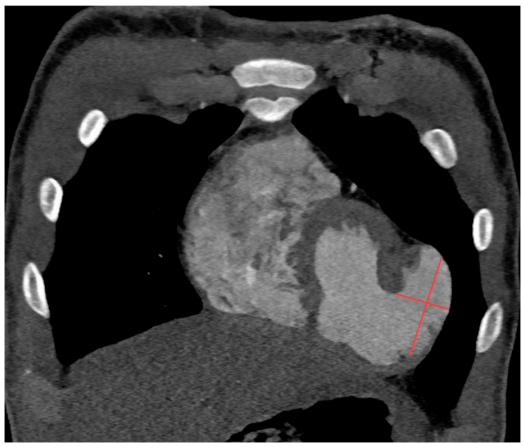
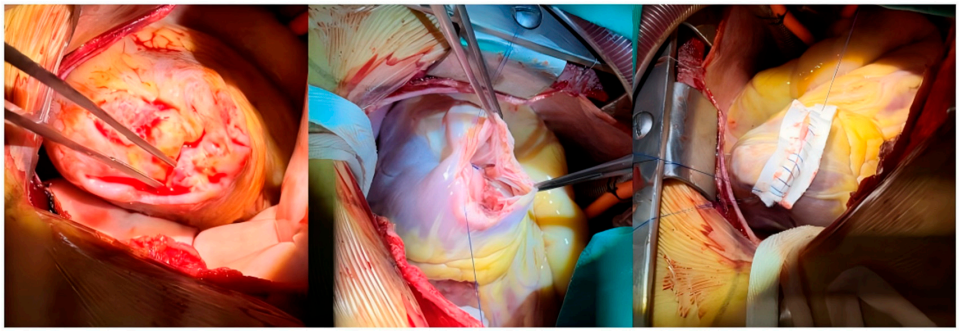


Figure 1: Computed tomography of left ventricular diverticulum. The right ventricular structure is normal. The left ventricle is enlarged, with thinning of the wall at the apex. A sac-like protrusion, measuring approximately 47 mm × 24 mm, is observed at the left ventricular apex. The interventricular septum is intact.

After completion of the preoperative evaluation, the patient underwent surgical repair under general anesthesia with mild hypothermic cardiopulmonary bypass and cardioplegic arrest. Intraoperative inspection revealed a left ventricular apical diverticulum measuring approximately 4.5 × 3.5 cm, with a markedly

thinned wall; the thinnest portion was approximately 2 mm. The diverticulum demonstrated fibrotic endocardial changes and systolic dyskinesia relative to the native left ventricle. After opening the diverticular sac, no organized thrombus was identified. The diverticular neck was closed with a bovine pericardial patch using continuous 5-0 polypropylene sutures. Following resection of the redundant diverticular wall, the remaining ventricular edges were reinforced in a sandwich fashion with two Teflon felt pledgets measuring approximately 1 × 1 cm and closed with continuous 4-0 polypropylene sutures (Fig. 2). During preoperative 3D surgical planning, particular attention was paid to preserving the adjacent coronary artery branches identified preoperatively (Fig. 3). After weaning from cardiopulmonary bypass, sinus rhythm was restored with one episode of electrical cardioversion. The total operative time was 165 min, with a cardiopulmonary bypass time of 69 min and an aortic cross-clamp time of 36 min. Intraoperative transesophageal echocardiography confirmed preserved left ventricular systolic function, complete exclusion of the diverticular cavity, absence of interventricular shunting, and no significant mitral regurgitation.



(**a**) (**b**) (**c**)

Figure 2: Surgical results of left ventricular diverticulum: (**a**) Collapse of the diverticulum following cardiopulmonary bypass. (**b**) Following incision of the sac to expose the diverticular neck, a pericardial patch was applied to exclude the neck. (**c**) The residual rim was closed using a felt patch in a buttressed closure technique.

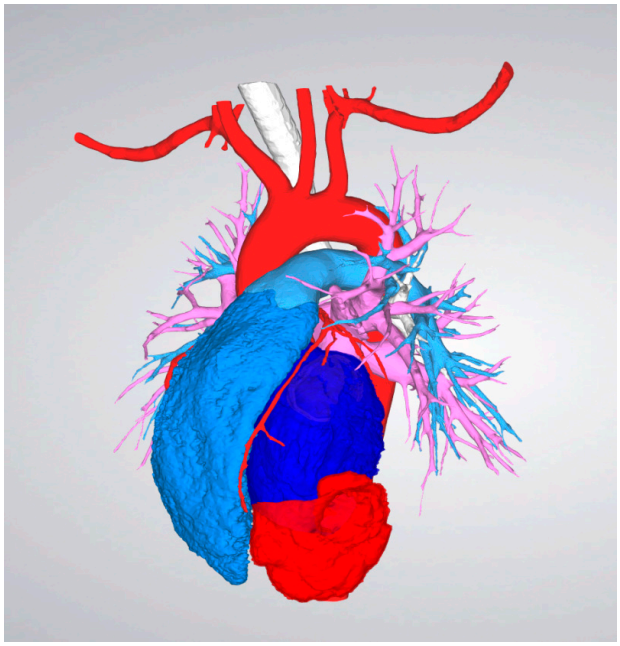


Figure 3: Three-dimensional reconstruction and scale model of a giant left ventricular diverticulum.

The postoperative course was uneventful. Hemodynamic parameters remained stable with only minimal vasoactive support, and no sustained ventricular arrhythmia was observed during the early postoperative period. Histopathological examination confirmed a fibrous diverticulum. At discharge, transthoracic echocardiography showed left ventricular ejection fraction (LVEF): 54%, left ventricular end systolic volume (LVESV): 37 mm, left ventricular end diastolic volume (LVEDV): 51 mm, and no mitral or tricuspid regurgitation. At the latest follow-up, 3 months after surgery, the patient remained free from exertional chest pain, palpitations, syncope, and thromboembolic events. Follow-up electrocardiography demonstrated sinus rhythm, and follow-up echocardiography showed LVEF: 56%, LVESV: 35 mm, LVEDV: 50 mm, and mild tricuspid regurgitation.

3 Discussion

Ventricular diverticulum is a relatively rare clinical disease, with a reported incidence of approximately 0.04% [2]. It can be classified as congenital or acquired. Congenital ventricular diverticulum primarily results from abnormal development of local myocardial tissue and the subsequent outward bulging due to intracavitary pressure. Its typical imaging manifestation is a localized, thinned, and bulging area of myocardium. Acquired ventricular diverticulum is most commonly attributed to factors such as impaired coronary perfusion or traumatic injury, which lead to localized thinning and outward bulging of the myocardial wall [3,4]. Ventricular diverticulum needs to be differentiated from diseases such as ventricular pseudoaneurysm, true ventricular aneurysm, ventricular pericardial hernia, and myocardial recess. Key differential features include the morphology of the lesion, the characteristics of the communicating orifice, the composition of the cavity, and the presence of paradoxical motion [5].

Conventional multimodality imaging remains the diagnostic foundation for ventricular diverticulum, but patient-specific 3D reconstruction adds incremental value when the lesion is large, anatomically complex, or located close to coronary branches. Prior literature has shown that 3D modeling and printing can improve spatial understanding, assist preoperative planning, support surgical simulation, and, in selected congenital heart disease cases, may refine the operative strategy and reduce unnecessary intraoperative exploration [6]. In the present case, dynamic 3D simulation was particularly useful because it clarified the diverticular neck geometry, estimated the residual ventricular cavity after exclusion, and improved appreciation of the lesion's relationship to adjacent coronary anatomy [7].

The patient had a history of short stature treated with growth hormone and concomitant scoliosis. In this case, these comorbidities were documented because they may influence perioperative assessment and long-term surveillance; however, the available clinical, imaging, and pathological findings did not support an acquired ischemic lesion, a traumatic lesion, or a secondary cardiomyopathic process. Instead, the apical location, narrow-necked sac-like morphology, paradoxical motion, and fibrous histology were most consistent with a congenital fibrous left ventricular diverticulum. Scoliosis was considered mainly relevant to perioperative positioning, respiratory management, and rehabilitation rather than to the primary etiology of the heart ventricular lesion.

Clinical diagnosis primarily relies on imaging. Transthoracic color Doppler echocardiography serves as an important non-invasive diagnostic tool, capable of clearly visualizing the morphology of the diverticulum, the size of the neck, the presence of thrombus, and local myocardial wall motion, thereby aiding differentiation from ventricular aneurysms. However, its utility in assessing local myocardial perfusion and surrounding coronary anatomy is limited. In such cases, cardiac CT and cardiac magnetic resonance (CMR) with perfusion imaging provide superior evaluation of regional myocardial blood supply [7].

The clinical management of a ventricular diverticulum depends on its characteristics. Asymptomatic patients with congenital diverticula can be managed with close follow-up. For those with associated arrhythmias, pharmacological control may be considered. If medication is ineffective, radiofrequency ablation guided by electrophysiological mapping represents a viable option. However, studies indicate a high recurrence rate post-ablation. For patients with refractory arrhythmias, renal denervation to reduce sympathetic tone has emerged as a potential novel therapeutic approach [8]. Because of its lack of myocardial contractility and frequent presentation with paradoxical wall motion, the fibrous type of diverticulum carries a significant risk of rupture and thrombosis, necessitating surgical resection in the majority of cases. While there is no standardized technique for managing the diverticular neck or the ventricular remnant, the overarching surgical principles involve isolating the diverticular cavity to prevent thromboembolism into the systemic circulation, resecting the sac to eliminate the risk of rupture, and meticulously preserving major coronary branches. Postoperative management focuses primarily on preserving the systolic function of the residual ventricle and monitoring for the occurrence of arrhythmias [9,10].

The key technical considerations for surgical resection involve not only the excision of the thinned myocardial tissue to prevent rupture and eliminate potential ectopic arrhythmogenic foci but also the secure closure of the diverticular neck to prevent recurrent bulging under high intracavitary pressure. The procedure is typically performed under mild hypothermic cardiopulmonary bypass with cardioplegic arrest. Preoperative planning is crucial to define the resection margins and identify critical coronary arteries. Closure of the neck can be achieved using various pericardial patch materials for intracavitary exclusion, with the specific choice often based on the surgeon's preference. The closure is commonly performed using a combination of interrupted and continuous sutures. Meticulous care must be taken to identify and preserve significant vessels near the edges to avoid iatrogenic injury and subsequent myocardial ischemia [11].

As a single case report, our findings must be interpreted with caution, as the experience gained from one patient may not be applicable to all others with similar conditions. We also acknowledge that the absence of a control group makes it difficult to determine precisely how much the use of 3D simulation added to the surgical planning beyond what conventional imaging could provide. Moreover, our follow-up period is relatively short, limiting our ability to comment on the durability of the repair or to determine whether the patient's arrhythmia will recur over the longer term. Ultimately, we believe that this approach holds promise, but further experience with additional cases and longer surveillance is necessary before its routine use can be recommended.

4 Conclusion

This case demonstrates that a giant congenital left ventricular diverticulum in an adolescent can be managed safely with individualized surgical reconstruction when diagnosis is established by multimodality imaging and operative planning is refined by patient-specific dynamic 3D simulation. Beyond confirming anatomy, dynamic 3D modeling may help define the resection margin, protect adjacent coronary branches, and support preservation of postoperative ventricular function. Further clinical experience is needed to determine which subsets of complex ventricular reconstructive cases derive the greatest benefit from this technology. Future multi-center studies with larger cohorts and extended follow-up are warranted to validate the long-term safety and functional benefits of this approach.

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Ethics Approval: The study is a single retrospective case report. Informed consent was obtained from the patient's legal guardians for the publication of this case and related images. Ethical approval was not required according to the institutional guidelines for single-case reporting. The CARE Checklist is attached as Supplementary Materials; Informed consent forms are available upon request. The study was conducted in accordance with the Declaration of Helsinki.

Conflicts of Interest: The authors declare no conflicts of interest.

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