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Research Article

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Left Ventricular Chamber Quantification Using Blender 3d Software

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ABSTRACT

Background: Accurate assessment of left ventricular (LV) size and function is essential in clinical practice. While cardiac MRI (CMR) is the reference standard, its limited accessibility restricts routine use. The study evaluated an open-source Blender 3D workflow for LV chamber quantification using conventional 2D echocardiographic views, validated against CMR.

Methods: Over 42 months, 172 CMR studies were screened - 25 patients were included for LV Volumetric analysis (apical cluster views) and 34 for LV Linear measurements (PLAX and 3 chamber views). Manual segmentation and semi-automated reconstruction were performed in Blender to derive LV end-diastolic (LVEDV), end-systolic (LVESV) volumes and standard linear dimensions (LVIDd, LVIDs, RVID, IVS, LVPW, AO, LA). CMR measurements served as reference. Agreement was assessed using correlation coefficients, Bland-Altman plots and Intraclass Correlation Coefficient (ICC [2,1]).

Results: For linear parameters, Blender showed strong correlation with CMR for LVIDd (r = 0.74, ICC = 0.45- 0.50) and LVIDs (r = 0.64, ICC = 0.43 - 0.50), moderate for RVID and IVS, and weaker for other parameters. For volumetric analysis, correlation was weak for LVEDV (r = 0.22, ICC = 0.26–0.42) and moderate for LVESV (r = 0.45, ICC = 0.36–1.7). Bland-Altman analysis showed minimal bias, with >50% of cases showing <25 mL difference versus CMR.

Conclusions: Blender-based LV quantification demonstrated reproducible, directionally consistent results, supporting its feasibility as a low-cost, open-source alternative for LV assessment in research and education.

Keywords
- LV Volumetric assessment is a basic parameter for cardiac assessment.
- 2D Echocardiographic examination is a basic investigation tool.
- High-End Echo machines and its related software are versatile but very expensive.
- Various 3D LV Models are processed, but none acceptable practically.
- Blender 3D Software or Test or BT is an open-source tool, used in a customized way.
- LV Chamber Quantification using 2D Echo data by Blender 3D Software choice in future.

Abbreviations

2D	:	2 Dimensional
2DE	:	2D Echocardiography
3D	:	3 Dimensional
3DE	:	3D Echocardiography
EDV	:	End Diastolic Volume
ESV	:	End Systolic Volume
LV	:	Left Ventricle
RV	:	Right Ventricle
IVS	:	Inter Ventricular Septum
LVIDd	:	LV Internal Diameter in diastole

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LVIDs	:	LV Internal Diameter in systole
RVIDd	:	RV Internal Diameter in diastole
IVSd	:	IVS in Diastole
LVPWd	:	LV Posterior Wall in Diastole
AOd	:	Aorta in Diastole
LAd	:	Left Atrium in Diastole
PLAX	:	Parasternal Long Axis view
ICC	:	Intraclass Correlation Coefficient
LVEF	:	LV Ejection Fraction
ECG	:	Electrocardiogram
ASE	:	American Society of Echocardiography
JPEG	:	Joint Photographic Experts Group
A3C, A4C, A2C	:	Apical 3, 4, 2 Chamber Views
PACS	:	Picture Archiving and Communication System
BT	:	Blender Technology
M - Mode	:	Motion Mode
MRD	:	Medical Record Department
IT	:	Information Technology
DIACOM	:	Digital Imaging and COMmunications in Medicine

Introduction

Accurate quantification of LV size and function is fundamental to cardiac diagnosis, risk stratification, and therapeutic decision-making. CMR imaging remains the reference standard for LV volumetric assessment due to its high spatial resolution and reproducibility. However, its limited accessibility, high cost, and longer acquisition times restrict widespread clinical use. In contrast, 2DE is more widely available and cost-effective but is limited by geometric assumptions, image quality dependence, and interobserver variability. Recent advances in open-source 3D modeling platforms offer opportunities to overcome these limitations by enabling 3D chamber reconstruction from standard 2D echocardiographic views. Blender, a freely available 3D software, provides robust modeling tools that can be adapted for medical image-based volumetric analysis.

Hypothesis

LV volumetric and linear measurements from Blender 3D reconstruction will demonstrate clinically acceptable agreement with CMR-based measurements.

Objectives:

(1) to validate LV end-diastolic and end-systolic volumes and linear dimensions obtained from Blender 3D software against corresponding CMR values and (2) to assess inter-method agreement and reliability using correlation analysis, Bland-Altman plots and intraclass correlation coefficients (ICC). This approach aims to establish a low-cost, reproducible, and open-source workflow for LV quantification suitable for both research and clinical applications.

Materials and Methods

Ethics Committee approval - A retrospective validation study was conducted at Apollo BGS Hospital, Mysuru, Karnataka, India, in accordance with the Declaration of Helsinki (1975, revised 2013). The study protocol was approved by the Institutional Ethics Committee for Biomedical Research, Apollo BGS Hospitals (NABH certification no. EC CT 2019 0114). In view of Retrospective analysis, consent was not considered.

Study Design

Retrospective Cohort Study.

Study Population

A total of 172 patients who underwent both echocardiography and CMR between August 2022 and August 2025 (42 months) were screened.

Criterias

Inclusion criteria (All must undergo 2DE and CMR with available good imaging data)

- Patients with adequate image quality

Exclusion criteria

- Poor acoustic windows
- History of prior cardiac surgery
- Acute myocardial infarction
- Patients with stable hemodynamic status
- Mechanically ventilated patients
- Significant arrhythmias

Image Acquisition

2DE was performed using Philips Affiniti 30 (version 9.0.3), GE Vivid 12.2, and GE Vivid 7.0.10 systems. CMR studies were acquired using Philips ACHIEVA 1.5T scanner (32469). Blender 3D Software version 4.5.2 LTS, an open-source platform freely available at www.blender.org, was used for image processing and reconstruction. Collectively called as Blender Test (BT) or Cardio Blender was developed and refined over 15 years for cardiac imaging research as an experimental tool. Learned through free internet tutorials with various versions (2.79 to 4.5.2 LTS).

2D Echo Protocol

The examination is performed with the patient in the left lateral decubitus position using a 2-5 MHz phased-array transducer, optimizing gain, depth, and sector width for clear LV visualization. ECG monitoring identifies end-diastolic and end-systolic frames. If image quality is poor, contrast echocardiography may be used per ASE guidelines. Standard 2D views (PLAX view and Apical Cluster Views - A2C, A3C and A4C Views) are acquired at ≥ 50 fps. At least three cardiac cycles (five in arrhythmia) are recorded and stored in DICOM format for offline analysis. Analysis is performed using vendor-specific or open-source software. End-diastolic and end-systolic frames are defined by maximal and minimal LV cavity size, respectively. Endocardial borders are traced in A4C, A3C and A2C views, excluding papillary muscles. Good image quality was defined by adequate gray scale resolution, clear delineation of endocardial borders, and absence of foreshortening. Biplane Simpson's method of discs calculates LV volumes. The software provides LVEDV, LVESV, and LVEF = (EDV - ESV)/ EDV × 100%, indexed to BSA when appropriate. Ensure no foreshortening, correct border tracing, and report LVEDV, LVESV, LVEF, frame rate, and method used. Reproducibility is assessed in at least 10% of cases.

Cardiac MRI protocol

The patient is screened for contraindications (pacemaker, metallic implants, claustrophobia). ECG gating ensures cardiac phase synchronization, and breath-hold training is provided. Scanning is performed supine using a 1.5T scanner with a cardiac phased-array coil. Scout images define cardiac axes. Cine imaging uses a steady-state free precession (SSFP) sequence (TR/TE ≈ 3.0/1.5 ms; flip angle 45 - 60°; slice thickness 6-8 mm; gap ≤ 2 mm; matrix ≈ 192×192). A contiguous short-axis stack from mitral annulus to apex covers the entire LV, with additional 2- and 4-chamber views. Temporal resolution is ≤ 40 ms per frame. Analysis is performed on dedicated software (e.g.: ISP). End-diastolic and end-systolic frames correspond to maximal and minimal LV cavity sizes. Endocardial borders are traced on each slice; papillary muscles and trabeculations are included in myocardial mass. LV volume is obtained by summing slice volumes. Derived parameters include LVEDV, LVESV, LVEF, LV Mass and indexed values. Ensure complete coverage, consistent contours, and report field strength, sequence type, temporal resolution, slice thickness and LV measurements. Reproducibility is tested in ≥ 10% of studies.

Image Preprocessing

All subjects must undergo 2D Echo and CMR. Available data must be suitable for Blender Test analysis. For both, ED and ES frames were selected from imaging data either by using mitral valve motion (opening and closing), LV maximal and minimal dimensions, or ECG gating. Frames were exported in JPEG format for further editing process.

Blender-Based Workflow for Linear measurements

Here ED and ES of PLAX still images from 2D echo (Figure 1A) and 3C stills images from CMR (Figure 1B) were studied as parameters represent similarly. To measure anything between 2 points, "leading-edge to leading-edge" method applied. This measures Distance, Diameter, Thickness and phasic changes during cardiac cycle at ED and ES were also noted. ED and ES of PLAX still images from 2D echo were imported into Blender. Measurements were performed using the "MeasureIt" add-on, present within Blender 3D software by enabling it. While studying 3C stills images from CMR, open the default software in two frame mode - so that we can see both ED and ES of 3C stills of CMR together. Then by using default "caliper", we can measure all parameters. RVID, IVS & LVPW thickness, AO and LVID were measured during ED while LVID and LA were measured during ES phase of cardiac cycle. In both the methods, more precise values can be obtained. Reproducibility, Reassessment and Recalculation is possible in a user-friendly way. In future, newer and easy parameters can be obtained after clinical validation.

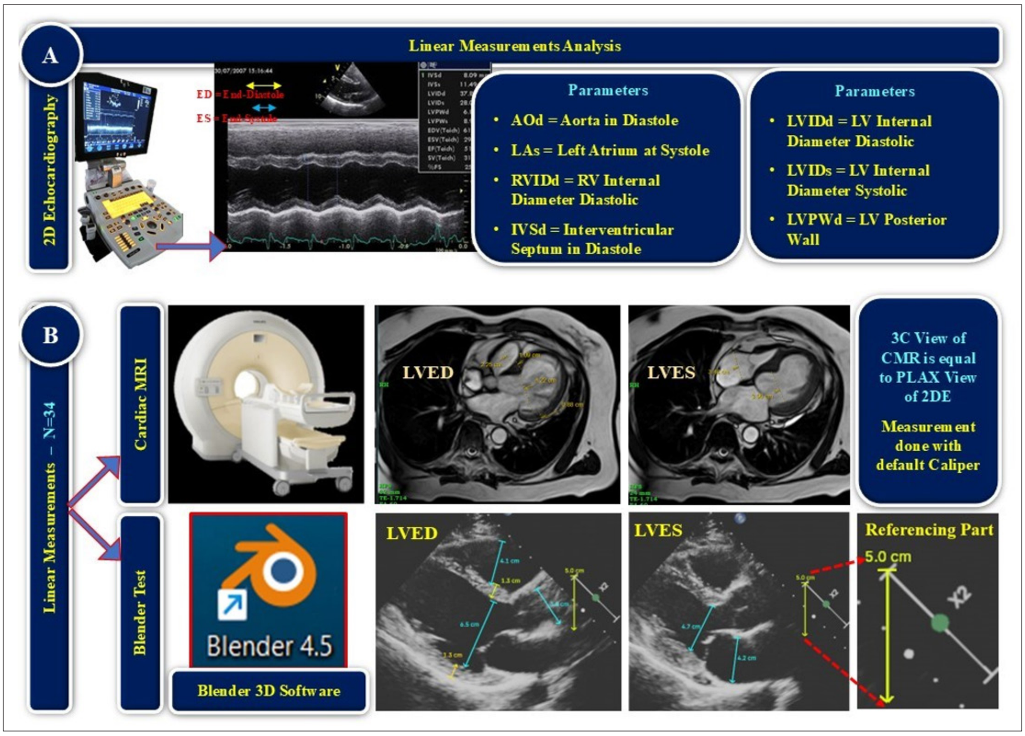

Figure 1: Left Ventricular Linear measurement assessments

A. Conventionally by 2D Echocardiography

B. By Cardiac MRI and Blender Test

Blender-Based Workflow for 3D LV Volume measurements

CMR is the standard golden method for LV Volume assessment. The final report of CMR includes - LV Volumes and other derived values in a customized way (Figure 2A). Here we are explaining getting LV volumes by using Blender 3D Software (Figure 2B). To start with - import ED and ES still images of 2D Apical clusters (A4C, A2C, A3C) views into Blender 3D Software workplace. Edit them separately. Endocardial borders were manually segmented, LV cavity isolated and surface extruded to form 3D mesh model. Group them into LVED and LVES groups. Further editing continued group by group. First LVED 3D models (of A4C, A2C, A3C) were taken and aligned at the center. Keep A4C 3D model at center (-00). Then apply specific rotation to A2C (-600) and A3C (-1200) 3D models to A4C 3D model. Then apply Boolean intersection modifier between A4C model - first with A2C and then A3C 3D models. This will generate single LVED 3D model. Similar workflow to be applied for LVES 3D models to get single LVES 3D model. The mesh smoothing and customized texture or color can be applied (Video 1). Then each 3D model was selected and respective LV Volumes were measured by using "3D Print add-on" of Blender 3D Software (by enabling it). Following correction formula applied:

Where,
m LVV = measured LV Volume from LV 3D still model in Blender Test
c LVV = calculated LV Volume = Final Volume
Stroke volume (SV = EDV - ESV) and Ejection Fraction (EF = SV/EDV × 100) were derived

If the measured LV Volume (m LVV) is in milliliter (ml) :

If the measured LV Volume (m LVV) is in Liter (L) :

c LVV = (m LVV (in ml) / 1000) X 25 + 45

c LVV = m LVV (in Ltr) X 25 + 45

Validation Strategy
Done with Blender vs. 2D echocardiography (M-mode) for Linear measurements and Blender vs. CMR (gold standard) for Volumetric analysis. All data were retrieved retrospectively from the institutional PACS system. All data were tabulated in Microsoft Excel. Agreement was assessed using Pearson correlation coefficients, Bland-Altman analysis and intraclass correlation coefficient (ICC [2,1], two-way random effects model). Statistical significance was set at $p < 0.05$.

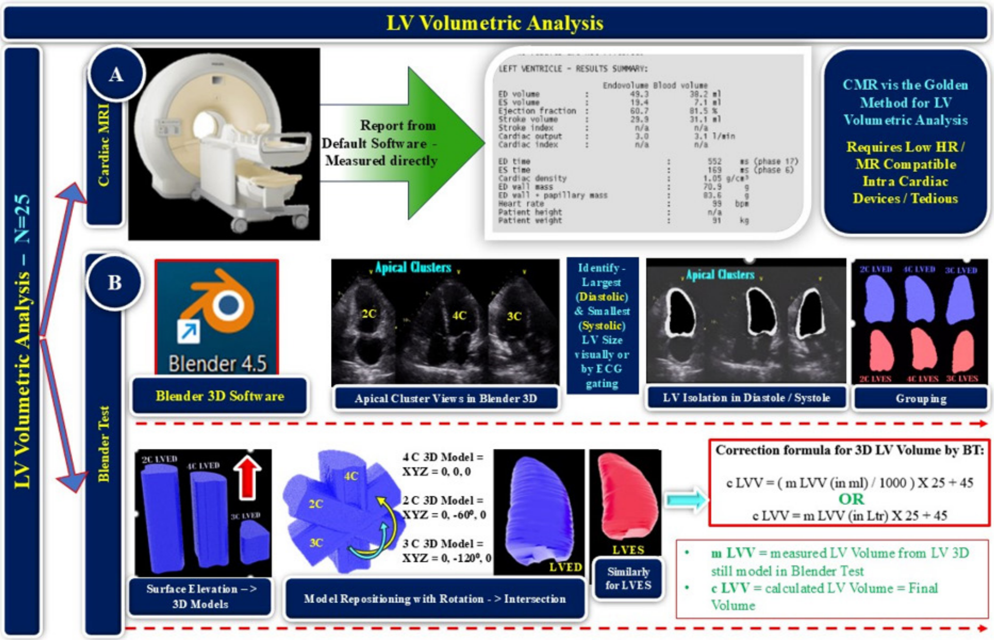

Figure 2: Left Ventricular Volume assessments
A. Conventionally by Cardiac MRI
B. By Blender Test or BT

Results
Had 172 cases of Cardiac MRI from Aug 2022 to Aug 2025 (42 months), filtered down as per required data availability with reasonably good quality imaging data. For Volumetric Analysis cohort, we had 25 patients with suitable image data. Of which 17 (68%) were males and mean age of 62.8 years with range of 45 - 77 years. For Linear Measurement cohort, we had 34 patients with suitable image data. Of which 19 (56%) were males at mean age 61 years (range of 21 - 83 yrs). Most cases were referred for myocardial viability testing.

LV Linear Measurements Analysis (Figure 3): Comparative analysis between CMR-derived and Blender Tool (BT)-derived LV linear parameters demonstrated variable degrees of correlation and agreement across measured indices. Among all parameters, LVIDd (r = 0.74; ICC = 0.45 - 0.50) and LVIDs (r = 0.64; ICC = 0.43 - 0.50) showed the strongest correlation and moderate inter-method reliability, indicating close agreement between BT and CMR measurements. RVID (r = 0.53; ICC = 0.41 - 0.49) and IVS (r = 0.49; ICC = 0.39 - 0.50) demonstrated moderate correlation and acceptable reproducibility. In contrast, AO (r = - 0.25; ICC = - 2.51/0.50), LA (r = 0.33; ICC = 0.31/0.49), and LVPW (r = 0.13; ICC = 0.17/0.50) exhibited weaker correlation, suggesting higher variability in these parameters. BAP (Figure 4 and 5) supported these findings, showing small bias and narrow limits of agreement (LOA) for most parameters. The bias values and LOA (upper, lower) were as follows: AO: -1.54 (-3.24, 0.87), LA: -0.83 (-2.37, 0.71), RVID: -0.45 (-1.50, 0.60), IVS: -0.45 (-1.11, 0.21), LVPW: -0.41 (-1.02, 0.20), LVIDd: -1.19 (-2.65, 0.28) and LVIDs: -1.26 (-3.07, 0.56). Overall, BT-derived LVIDd and LVIDs demonstrated the highest degree of agreement with CMR, whereas wall thickness & chamber dimensions showed moderate - weak correspondence.

3D LV Volumetric Analysis (Figure 6A) - Volumetric comparison between CMR and Blender Tool (BT) derived datasets revealed moderate agreement with variable correlation strengths across parameters. For **LVEDV,** correlation was weak (r = 0.22) with ICC values of 0.26 (subjects) and 0.42 (methods). For **LVESV,** correlation improved moderately (r = 0.45), with ICCs of 0.36 (subjects) and 1.70 (methods). **BAP (Figure 6B and 6C)** demonstrated acceptable bias and dispersion, with more than 50% of cases showing <25 ml difference between BT and CMR-derived volumes. Bias and LOA (upper, lower) were as follows: LVEDV: 20.22 ml (-83.56, 123.99), SD = 52.95 and LVESV: -4.17 ml (-78.82, 70.49), SD = 38.09. These findings indicate moderate inter-method consistency, particularly for LVESV and suggest systematic underestimation of LVEDV by the Blender-based workflow.

Summary of Statistics of LV Linear Measurements

Para-meters	(Mean ± SD)		r	ICC		Bland-Altman Plot				Agreement
	CMR	BT	Correlations	Subjects	Methods	Bias	LLOA	ULOA	SD	
AO (cm)	2.31 ± 0.55	3.83 ± 0.55	-2.50	-2.51	0.50	- 1.54	- 3.24	0.15	0.87	Poor
LA (cm)	3.42 ± 0.51	4.25 ± 0.79	0.33	0.31	0.49	- 0.83	- 2.73	0.71	0.79	Poor–Moderate
RVID (cm)	2.63 ± 0.50	3.08 ± 0.59	0.53	0.41	0.49	- 0.45	- 1.50	0.59	0.54	Moderate
IVS (cm)	1.11 ± 0.23	1.56 ± 0.35	0.49	0.39	0.50	- 0.47	- 1.11	0.21	0.34	Moderate
LVPW (cm)	0.91 ± 0.19	1.31 ± 0.28	0.13	0.17	0.50	- 0.41	- 1.02	0.20	0.31	Poor
LVIDd (cm)	4.76 ± 0.73	5.95 ± 1.22	0.74	0.45	0.50	- 1.19	- 2.65	0.28	0.75	Strong
LVIDs (cm)	3.56 ± 0.95	4.83 ± 1.20	0.64	0.43	0.50	- 1.23	- 3.07	0.56	0.93	Moderate–Strong

Figure 3: Summary of Statistics of LV Linear Measurements

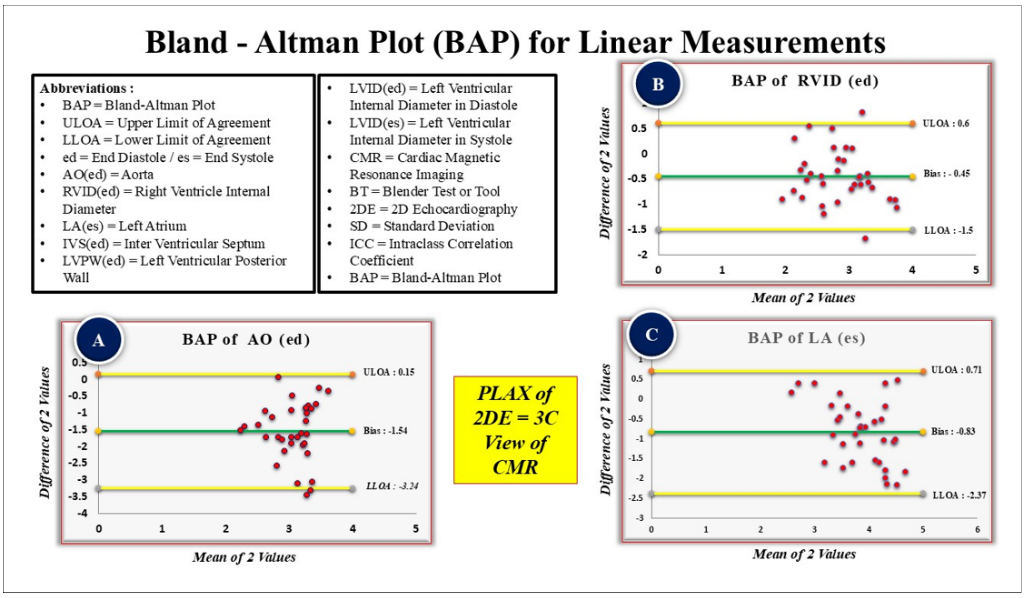

Figure 4: Bland-Altman Plot for AO, LA and RVID

Discussion

General: The quantification of Cardiac Chambers is the corner stone of cardiac imaging. 2D Echocardiography is the most commonly used imaging modality, because of its availability and porftability. Assessment of left ventricular (LV) size and systolic function is vital in nearly all cardiac evaluations. Echocardiography measures LV dimensions, wall thickness, end-diastolic and end-systolic volumes and mass to estimate systolic performance. While M-mode offers superior temporal resolution, 2D imaging provides better anatomical alignment (especially in TEE). Accurate LV diameter measurement requires a perpendicular imaging plane and modern practice now favours inner edge - to - inner edge measurements due to improved spatial resolution, ensuring precise cavity size estimation. Various methods established for endocardial border delineation, of which Enhanced echocardiography using contrast significantly improves EF accuracy, enhances agreement with MRI, and achieves inter-observer reliability comparable to MRI, making contrast echocardiography a superior option for 2D Echo LVEF assessment. LV Foreshortening occurs when the LV long axis is improperly imaged, leading to underestimation of its true length. Proper imaging requires a stationary apex throughout the cardiac cycle and adjustment of the probe to true long-axis view. Measurements of end-diastolic and end-systolic dimensions should align with ECG signals for consistency - systole at the QRS peak and diastole just before it - ensuring standardized timing over visual estimation [1-4].

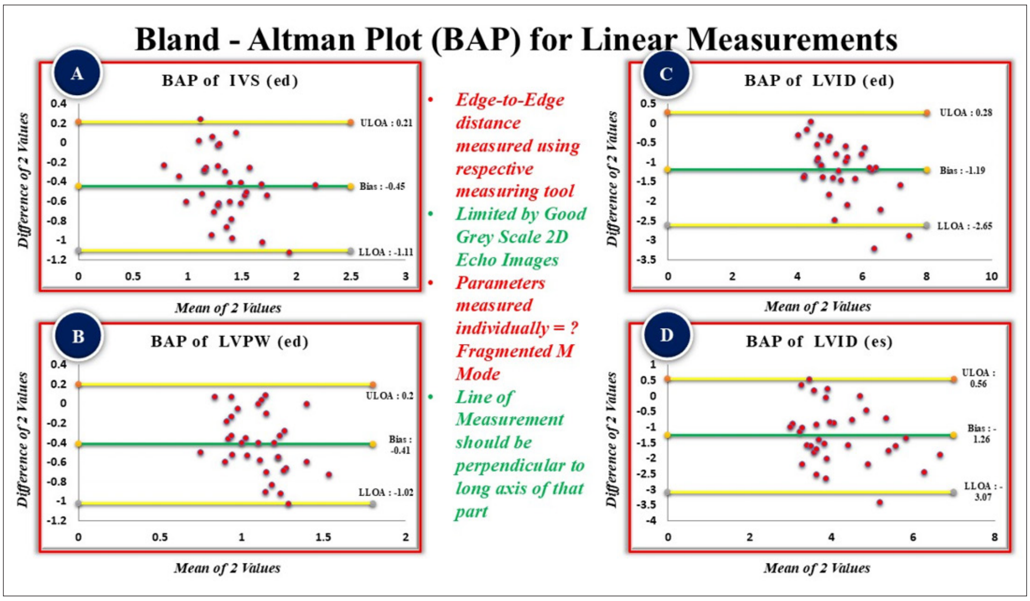

Figure 5: Bland-Altman Plot for IVS, LVPW, LVIDs and LVIDd

A **Summary of Statistics of LV Volumetric Measurements**

Para-meters	(Mean ± SD)		r	ICC		Bland-Altman Plot				Agreement
	CMR	BT	Correlations	Subjects	Methods	Bias	LLOA	ULOA	SD	
LVEDV (ml)	142.13 ± 40.65	119.45 ± 39.51	0.22	0.26	0.42	20.22	- 83.56	123.99	52.95	Poor
LVESV (ml)	82.45 ± 43.02	85.77 ± 24.03	0.45	0.36	1.70*	- 4.17	- 78.82	70.49	38.09	Poor - Moderate

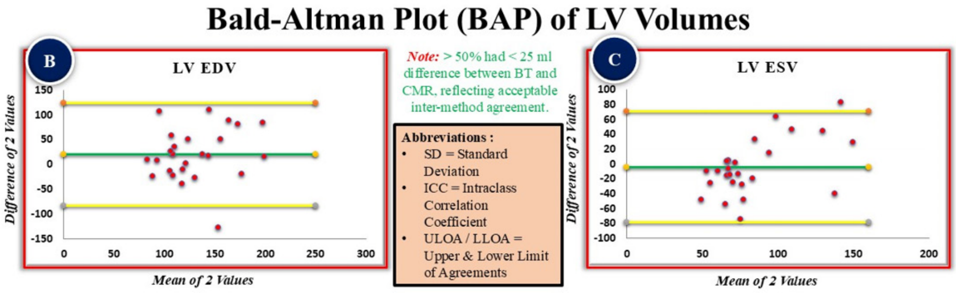

Figure 6: Bland-Altman Plot and Summary of Statistics of LV Volumes

2D Echocardiography further developed to 3D echocardiography, which eliminates geometric assumptions and is less affected by off-axis imaging errors or ventricular asymmetry. It provides better accuracy in abnormal ventricles, is more reproducible for serial assessments, and offers improved analysis in regional wall motion defects. But 3D Echo requires high-quality 2D images, advanced equipment and has lower temporal and spatial resolution than 2D echocardiography, limiting use in arrhythmic patients. Next comes Real-time 3D transesophageal echocardiography (RT 3D TEE) provides detailed anatomical visualization of cardiac structures and pathologies, enhancing physician communication and diagnostic accuracy, particularly for stenotic and regurgitant lesions. Hence Real-time 3D echocardiography (3DE) has proven to be accurate, reproducible and versatile, often outperforming 2D echocardiography in prognostic value and clinical outcomes. Although the adoption of 3D echocardiography has been limited by time and expertise, automated quantification and AI-assisted software have improved both accuracy and efficiency.8 Compared with cardiac MRI, 3DE slightly underestimates left ventricular (LV) volumes by less than 20 mL but shows comparable EF values. Fully automated 3DE analysis enables practical, reproducible and routine LV quantification with excellent correlation to MRI, offering a reliable, efficient alternative for clinical assessments despite image quality variability. An automated method has been developed to generate a three-dimensional (3D) model of the LV from multiple-axis echocardiography (echo). Image data from three long-axis sections and a basal section is processed to compute spatial nodes on the LV surface. The generated surfaces are output in a standard format such that it can be imported into the curvilinear-immersed boundary (CURVIB) framework for numerical simulation of the flow inside the LV. The 3D LV model can be used for better understanding of the ventricular motion and the simulation framework provides a powerful tool for studying LV flows on a patient specific basis. Future work would incorporate data from additional cross-sectional images.

Cardiac MRI remains the gold standard for assessing cardiac volumes and function because it avoids geometric assumptions inherent in 2D echocardiography. Cardiac MRI with its multiplanar and 3D reconstruction capabilities, is especially valuable for visualizing complex baffles and conduits in congenital heart surgery when echocardiography or angiography are insufficient. Its few limitations include incompatibility with pacemakers or metallic implants, difficulty in patients with arrhythmia or claustrophobia and the need for patient immobility during scanning. Despite these, MRI remains essential for detailed anatomical assessment in complex cardiac cases. Also limited by high cost and limited availability restrict routine clinical use.10 Two-dimensional echocardiography had variations of ±15% for LVEF measurement compared with cardiac MRI. Three-dimensional echocardiography had better agreement with cardiac MRI and should be used as first-line imaging. Advances in four-dimensional imaging, computational modeling, and simulation technologies now enable detailed, patient-specific analysis of cardiac hemodynamics. Since cardiovascular disease is closely linked to blood flow patterns, computational modeling bridges gaps left by current diagnostic tools, providing deeper physiological insights. Using anatomical data from echocardiography, MRI, or CT, these models simulate blood flow within the heart chambers. Such non-invasive simulations are emerging as cost-effective, high-fidelity tools for improving diagnosis, treatment, and understanding of cardiovascular disease [5-13].

We discovered, experimented over 15 years by our own indigenously developed method and first time introduced called as “Blender Test” or “BEST Test”, by using Blender 3D Software. “BEST Test” - means B = Brightness or B Mode, E = Enhanced, S = Simulations and T = Transformations. This is the first time ever introduced in Cardiology Imaging - as an offline imaging process [14]. This is open-source 3D software, freely downloadable at www.blender.org, released under General Public Licence (GPL) [15]. Complete process of 3D surface modelling, learned by using numerous free online tutorials since last 15 years. The most important and reputable websites for free Blender tutorials include the official Blender site, Blender Guru and CG Cookie and many more [16-19]. Over a period of time after repeated experimenting, we succeeded in getting 3D model from 2D data sets. Under methodology section, we explained Blender 3D software workflow for LV chamber quantification with conventional 2D echo datasets. Then values of each parameter validated against Cardiac MRI (a gold standard). Then all the data were statistically analysed. 6The Linear measurement analysis demonstrated strong agreement for LVIDd and LVIDs, moderate consistency for RVID and IVS, and weaker correlations for AO, LA, and LVPW. These trends likely reflect the dependence of Blender-based linear extraction on 2D image quality, manual border identification and inherent differences between imaging modalities. Despite these limitations, bias in Bland-Altman analysis remained within clinically acceptable limits for most parameters, supporting reproducibility. In the Volumetric assessment, LVESV showed moderate correlation and reasonable ICC, while LVEDV exhibited weaker correlation, likely due to underestimation from 2D-derived 3D reconstruction compared with true 3D CMR segmentation. Nonetheless, over half of the measured cases showed < 25 ml difference between methods, indicating acceptable agreement for practical applications. Collectively, the findings highlight the potential of the Blender 3D platform as a low-cost, open-source alternative for LV quantification, providing clinically relevant approximations to CMR-derived parameters. The tool demonstrates particular promise for educational use, early research validation, and in settings where advanced imaging modalities are not readily available. This software works without the need for proprietary software. This is especially valuable in resource-limited settings where access to advanced echocardiographic or MRI software is restricted. The differences between 3D Echocardiography, Cardiac MRI and Blender Test shown in Figure 7.

Aspect	3D Echocardiography (3DE)	Cardiac MRI (CMR)	Blender 3D (from 2D Echo)
Source Data	Real-time volumetric ultrasound (3D or 4D dataset)	Multiple tomographic slices (short-axis, long-axis)	2D echo images (A4C, A2C,A3C) manually segmented
Data Type	Native 3D voxel data	Stacked 2D slices → 3D voxel volume	2D contours → surface mesh
Segmentation Basis	Automated or semi-auto endocardial surface detection within 3D echo volume	Manual or AI-based contour tracing per MRI slice	Manual landmark-based tracing in 2D planes
Model Generation	Software interpolates directly within 3D ultrasound voxel volume to form surface mesh	3D surface reconstructed by stacking and interpolating contours from slices	LV contours manually isolated, Surface elevated, Geometrically aligned, Boolean Intersection creates single mesh 3D model.
Coordinate System	Intrinsic to 3D probe volume	MRI DICOM spatial coordinates	User-defined alignment
Accuracy	Limited by spatial & temporal resolution; angle-dependent	High spatial accuracy; gold standard for LV geometry	Dependent on segmentation precision & interpolation method
Surface Representation	Triangular mesh extracted from ultrasound voxels	Polygonal mesh from MRI segmentation masks	Blender polygonal mesh (procedurally modeled)
Output Volume Calculation	From mesh or directly from voxel integration	From enclosed contour volumes	Blender 3D volume calculation tools
Automation	High (commercial echo systems: GE, Philips)	Semi-auto (e.g., CVI42, Segment, Medis Suite)	Manual / Semi-automated (scripts or Python in Blender)
Visualization Quality	Moderate (due to ultrasound speckle)	Excellent anatomical fidelity	Fully customizable, aesthetic, exportable for teaching / research
Main Limitation	Lower spatial resolution, shadowing artifacts	Expensive, time-consuming	User-dependent geometry, approximate interpolation, No Artifacts

Figure 7: Summary of differences between 3D Echocardiography, Cardiac MRI and Blender Test.

Clinical Implications - BT demonstrated reasonable accuracy for linear measurements, supporting its use as an adjunct in chamber size assessment. Volumetric quantification requires further optimization but shows promise for integration into low-cost workflows. Open-source solutions may enhance reproducibility, reduce dependency on vendor-specific tools, and provide educational value for training in 3D reconstruction.

Limitations: We confess that, we tried to apply for publication in Heart India Journal and Journal of the American Society of Echocardiography (JASE) twice - Ref.: Ms. No. JASE-13486 and Ref.: Ms. No. JASE-13731 from the initial stages of Manuscripts writing. Observed to be limited by Small Sample Size, Financial constrain, Incomplete data storage, Poor-quality of the original imaging data, Operator dependency due to manual segmentation, Foreshortening, Semi-automatic workflow, increased time gap between 2D echo & CMR image acquisitions - so can't to do comparative analysis between 2D Echo and CMR pf same patient. Hence lot of data were rejected. Following are peer reviewer's advices - Manuscripts readability, User-friendly format for Results section, Increase the Sample size, Better Statistics, Increased Discussion part, Volume estimation corrected, Automation process on the way, No. of References increased, Quality of Imaging data from both 2DE and CMR and there should be universal protocol application and minimizing long duration between 2DE and CMR.

Note: 3D LV Volumetric reconstruction done in CMR by indirectly tracing the LV border and image directly in BEST test. CMR directly measures LV volume automatically, where as BEST Test require semiautomatic as mentioned earlier.

Linear measurement: we considered that 3C View of CMR is said to be equivalent to PLAX View of 2D Echo - confirmed with Senior Consultant Radiologist. In general, PLAX view measurements in ED and ES were done during 2D M Mode evaluation. Similarly CMR on offline provides - similar parameter measurements using caliper from CMR software itself. But during CMR evaluation - similarly we can measure offline by using to get most accurate. Then both Linear measurement values were statistically analysed.

Volumetric measurement: Limited by clarity on Endocardial border and Foreshortening. Method already explained. CMR considered to Gold Standard method for Volumes and measured directly. Then Volumetric values of 2D Echo and CMR were statistically analysed.

Future Directions: May have new parameters, that will be user friendly and clinically more validated. (ex. Myocardial Foot Print). Future work should focus on prospective datasets, automated segmentation methods and integration of machine learning tools to improve reproducibility and volumetric accuracy. This project is an example of combination of art and science. Its future prospectus depends on creativity and level of understanding of new versions of Blender 3D software by the operator. Planning to have Patency on the subject, but wish to make it freely available to entire world, probably by using cloud-based technology in future. Work on Color Flow Doppler and Pressure Gradients will be our future targets.

Learning Points

- **"LV Foreshortening"** - All Apical Cluster Views has one common point, ie. LV Apex, normally does not move during cardiac cycle. The degree of Apical movement suggests degree of "LV Foreshortening"
- **"Inter-views relationship"** at center - consider 4C View as baseline (ie. XYZ = Zero degree), 2C View is -60 degree to 4C View (ie. XYZ = 0, -600, 0) and 3C view is -120 degree to 4C View (ie. XYZ = 0, -1200, 0). These values are considered with respect to Ultrasound probe position during 2D Echocardiographic examination
- **"Endocardial border enhancement"** - Done with special system called "Shader Node System" which can create anything by altering image geometry, contrast and color. This can create customized "Realistic image", but at the cost of loss of surface. Here this results in increased dimensions (like LVIDd) and decreased thickness (like IVSd).
- **"Freedom of Imaging Expression"** - Customized unlimited imaging output like High-Definition images, 3D printing and so on is possible. Done with Zoom - in & out, Panning, Camera & Lighting setup, and so on. So, the report can be generated in a customized way.
- **"Frame Rate controlled"** - Any clip or 2D Echo clip is made up of sequential arrangements of 2D stills. To the camera, these still frames appeared one after the other, resulting in sense of motion picture. This occurred in a particular speed. The rate at which these still frames is called "Frame Rate". Conventional 2D Echo examination does not have any control over the Frame Rate. But

with BT, all clips are Frame Rate independent. So even 2D Echo clip of those with tachycardia, images are better visualised by controlling the Frame rate.

- **"Précised Measurement"** - We can measure any distance (length, breadth, height, diameter, thickness), curve, angle, area, volume etc.at any stage of the cardiac cycle. Precision depends on number of points (vertices) available on that reference image, which can be manually controlled.
- **"DECg test"** - Also called as Digital Echo-Cardio-graphy Test. Here same 2D Echo clip can be Reassess, Remeasure, Recalculate any clinically significant 2D echo parameters. This can avoid inter & intra - hospital Report variability, Customized viewing and Reporting by the consultant, etc. This may avoid future legal viability and improve inter-hospital relationships. Will save both money & time to patients too.
- **"Fragmented M mode"** - Here each parameter measured separately, unlike over the straight imaginary line during routine M Mode examination. One must consider that "the line of measurement should be perpendicular to central axis of the structure or cavity of examination part". Values are obtained against the standardization. Although comparatively little tedious, but will get more accurate or précised values. These values can be presented in a customized at the final report.
- **"New Parameters and Future abilities"** - Some of the newer, simpler and validated parameters can be created in a customized way (like Myocardial Foot Print - a graphical representation of transformation of 3D models of 3D LVEDV to 3D LV ESV, LV Twist, etc.). Will already applied for "Patent" issue. Planning to create "a Free Website" for direct operations from anywhere in the world with few clicks. The final spectrum of activity will be limited only by operator's creativity, skill & upgraded knowledge on newer versions of Blender 3D.

Conclusion

This study demonstrates that an open-source Blender 3D workflow can be successfully applied to left ventricular chamber quantification using conventional 2D echocardiographic datasets. **Linear measurements** derived from Blender showed strong correlation with CMR for LVIDd and LVIDs, indicating reliability for assessing LV cavity dimensions. Moderate correlations were observed for RVID(ed) and IVS(ed), while weaker correlations were seen for AO(ed), LA(es), and LVPW(ed). **Volumetric analysis** showed weaker correlation with CMR ($r = 0.22$ for LVEDV and $r = 0.45$ for LVESV), although over half of the cases demonstrated a difference of < 25 ml compared to CMR. These findings suggest that Blender is currently more robust for **linear dimension assessment** than for volumetric reconstruction when applied to 2D echo data. The workflow holds promise as a **low-cost, open-source tool** for clinical support and education, especially in resource-limited settings. Further refinements, particularly automation of segmentation, prospective validation and improved dataset integration - are needed before volumetric quantification can approach the reliability of CMR.

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Author's Contributions

Dr. Chandra Shekara Reddy (First and corresponding author) provides conceptualization, experimentation, protocol creation & execution, data collection & archiving, quality checking, manuscript preparation, editing and final submission. Normally, 2D Echo examination was done by In-hospital's Echo Lab team - guided by Dr. Arun Srinivas and Dr. Guru Prasad - Senior Consultant Cardiologists and clears all 2D Echocardiographic related queries. Cardiac MRI examination was done by In-hospital's Radiologist's team - guided by Dr. Vijay - Senior Consultant Radiologist guides and clears all Cardiac MRI related queries. Dr. Siddarth Kumar Chawath helps in article proofing, guidance for journal selection and submission.

Conflicts of Interest

8a. Financial support and sponsorship - None

8b. Conflicts of interest - There are no conflicts of interest.

Declaration of generative AI and AI-assisted technologies: During the preparation of this project work the authors used "CHAT GPT4" - an AI tool in order to get customized Python Script Coding lines for 2 reasons. Reason 1 - For repeated similar workflow and Reason 2 - For Manuscript Summary, Content organization and Improving language and Readability. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article. Never used for any critical thinking, expertise and evaluation.

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