My Approach to Calculate the Left Ventricular Ejection Fraction: From a Two-Dimensional to a Three-Dimensional Technique

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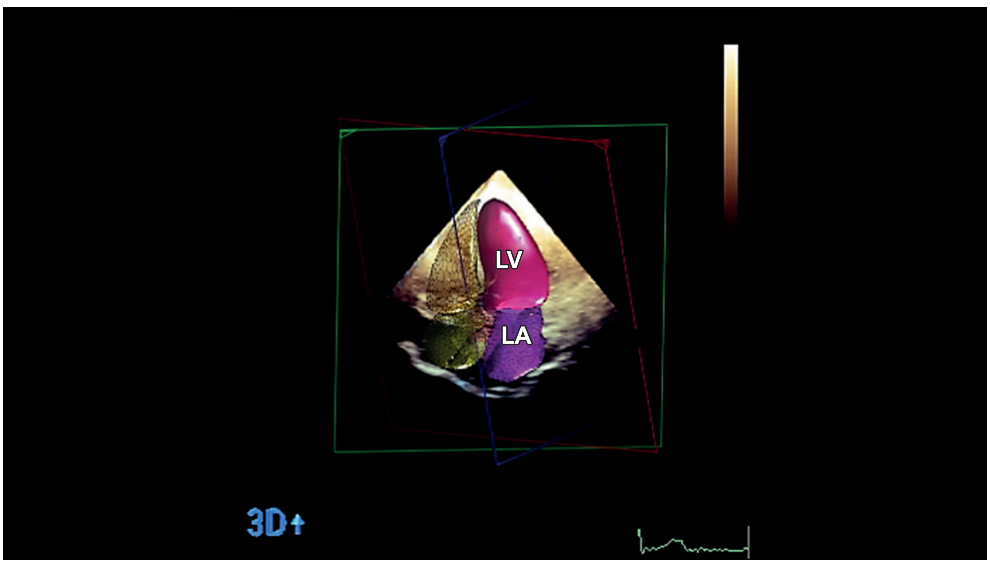
Central Illustration: My Approach to Calculate the Left Ventricular Ejection Fraction: From a Two-Dimensional to a Three-Dimensional Technique



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Abstract

Echocardiography is the most used diagnostic method for measuring left ventricular systolic function indices. It is possible to estimate, in a quick, available, and non-invasive way, parameters such as ventricular volumes, stroke volume, and ejection fraction. Being an expert in the technique is quite important to estimate these parameters accurately. Being able to refine the technique constantly is also important, and this is closely associated with the examiner's experience and knowledge of the current software solutions.

Keywords

Stroke Volume; Echocardiography; Three-Dimensional Echocardiography

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In this review article, we will discuss how to accurately measure left ventricular volumes and their ejection fraction using two-dimensional (2D) and three-dimensional (3D) echocardiographic techniques. We will also outline tips and suggestions based on the main North American and European guidelines for quantifying heart chambers and the most recent articles in the literature.

Introduction

In the early days of echocardiography, based on the one-dimensional method (M-mode), it was only possible to measure the end-diastolic and end-systolic diameters of the left ventricle (LV). Also, the end-diastolic and end-systolic volumes of the LV, the systolic ejected volume (stroke volume), and the ejection fraction were calculated using mathematical formulas strongly influenced by geometric assumptions. Furthermore, the M-mode, despite its excellent temporal resolution, was performed completely blindly, which often led to an overestimation of ventricular diameters and left ventricular mass.[1]

With the evolution of the technique and the use of two-dimensional (2D) echocardiography, it was possible to measure ventricular diameters in their true axis (perpendicular to the longitudinal axis of the LV), reducing the interobserver variability of their measurements. However, measuring ventricular volumes was still very dependent on mathematically pre-determined geometries. Over the years, techniques that trace the outline of the blood-tissue interface from apical 2-chamber (2C) and 4-chamber (4C) views, such as the area-length method and the biplane disc summation technique, were made available to measure LV end-diastolic and end-systolic volumes. Although they are still based on geometric assumptions and the frequent shortening of the LV apical region, such techniques can correct geometric distortions not visible in a long-axis parasternal section by allowing the analysis of a much larger number of ventricular segments.[2]

At the beginning of the 21st century, with the availability of advanced echocardiography techniques, most of the existing limitations in measuring ventricular volumes were eliminated. With the introduction of echocardiography with microbubble-enhanced ultrasound, it became possible to identify the compact blood-myocardium interface better and then trace the endocardial borders more accurately. Consequently, it was possible to measure volumes with less underestimation, finding values closer to those found in nuclear magnetic resonance imaging. Its applicability for opacifying the left ventricular cavity was already approved by the US Food and Drug Administration (FDA) in 2014 and has been used frequently in most of the world's largest echocardiography centers in patients who have suboptimal echocardiographic windows.[3] With the evolution of three-dimensional (3D) echocardiography, it became possible to estimate left ventricular volumes without any geometric assumptions, eliminating the apical shortening bias. Robust studies in the literature have already demonstrated its importance for measuring LV ventricular volumes, left ventricular mass, and ejection fraction, with values being very close to those found by the gold standard technique, which is nuclear magnetic resonance imaging.[4]

In recent years, the use of artificial intelligence has grown substantially. Software solutions now have mathematical algorithms, and these algorithms can easily, quickly, and reproducibly estimate left ventricular volumes, stroke volume, and ejection fraction, both through 2D and 3D echocardiography, reducing interobserver variability, especially in less experienced examiners.[5]

In this article, we will discuss how to accurately measure left ventricular volumes and their ejection fraction using 2D and 3D echocardiographic techniques, paying special attention to the main details that can lead to measurement errors.

2D Echocardiography

The American Society of Echocardiography (ASE) and the European Association of Cardiovascular Imaging (EACVI) guidelines for quantifying cardiac chambers recommend measuring the end-diastolic and end-systolic diameters of the LV during echocardiographic but do not suggest that these diameters be used to measure ventricular volumes, especially in ventricles with changes in their geometry and changes in segmental myocardial contractility. The technique based on conventional 2D echocardiography recommended for estimating LV volumes, stroke volume, and ejection fraction is the biplane disc summation technique (modified Simpson's rule).[2,6]

Using this technique, from apical 4C and 2C views, it is possible to visualize 13 of the 17 LV segments, correcting potential geometric distortions that may involve its apical regions and inferoseptal, anterolateral, anterior, and inferior walls. Furthermore, it has the advantage of measuring volumes that take on a form that is less based on geometric assumptions than the volumes quantified from simple linear diameters of the LV, as in the cube and Teichholz techniques. As a disadvantage, the biplane disc summation technique does not allow the inclusion of changes in myocardial contractility that may affect the anteroseptal and inferolateral walls of the LV, as seen in the apical 3-chamber view. It also has a limitation involving frequent endocardial dropout, which makes tracing the compact blood-myocardial interface difficult, especially in suboptimal echocardiographic windows.[2]

To measure left ventricular volumes using the biplane disc summation technique, apical 4C and 2C views must be obtained. Shortening of the apical region of the LV should be avoided as much as possible, and spatial and temporal resolutions should be optimized to identify better the myocardial segments studied. In adults, we choose to use second harmonic frequency waves to better differentiate the myocardial trabeculae from the endocardial border and reduce ring-down artifacts. In obese individuals, the frequency should be reduced to optimize the image being obtained.[7]

After acquiring the clips, with conventional software present in echocardiography devices of different brands, the image must be frozen at the end of the diastole, which will correspond to the peak of the R wave of the electrocardiogram, immediately after the closure of the mitral valve.[8-10] You must begin marking the endocardial border (blood-tissue interface) of the medial mitral annulus along the entire left ventricular cavity to the lateral mitral annulus or vice versa. During this process, it is important to ensure that the marking stops at the mitral annulus and does not invade the ventricular surface of the mitral valve leaflets. The trabeculae corresponding to the non-compacted area of the myocardium, as well as the papillary muscles and the chordae tendineae, must be included in the volumetric quantification. If there are images compatible with thrombi or masses inside the LV, these must also be included in the volumetric quantification. After volumetric measurement at the end of the diastole, the end-systolic volume is measured, which must be taken after the T wave of the electrocardiogram at the moment when the smallest systolic ventricular volume is visually observed. The measurement of LV end-diastolic and end-systolic volumes must be made in the apical views of 4C and 2C (Figure 1).[2,6]

After carrying out these measurements, the echocardiography device's software will calculate the end-diastolic and end-systolic volumes in 4C, 2C, and biplane and estimate the biplane stroke volume and the biplane LV ejection fraction. The normal values for parameters of LV dimensions, volumes, and ejection fraction validated in the ASE/EACVI guidelines and in the most recent published multicenter study, the WASE (World Alliance Societies of Echocardiography) study, are shown in the Table 1.[11-14]

Semi-automated software has recently emerged to make these measurements faster and reduce interobserver variability. Nevertheless, these solutions are very dependent on an excellent echocardiographic image and require expertise and training. After acquiring apical 4C and 2C views, the software recognizes the moment of the end diastole (peak of the R wave) from the electrocardiogram. It requires the ventricular basal endocardium next to the mitral annulus and the ventricular apex to be marked. Therefore, it automatically traces the endocardial border, measuring the end-diastolic volume and allowing the necessary fine-tuning after measurement. Subsequently, the software will automatically quantify the end-systolic volume (at the end of the T wave of the electrocardiogram) and calculate the volume-time curve of the LV based on the volumetric variation of the left ventricular cavity based on the tracing of the endocardial border, frame by frame. The trace of the endocardial border can also be fine-tuned at the end of systole. Once the analysis is complete, the software provides information such as biplane end-diastolic and end-systolic volumes, biplane stroke volume, and LV ejection fraction (Video 1).[2,6]

Microbubbles as Ultrasound Contrast Agents

In echocardiography laboratories and intensive care or emergency room environments, patients with suboptimal echocardiographic windows are common. This makes it very difficult to estimate LV volumes accurately. In this scenario, the applicability of microbubbles as an ultrasound contrast agent (ARUS) has increased dramatically over the last decade. The most recent ASE guidelines on the use of ARUS recommend that, in cases where 2D resting echocardiography cannot be used to visualize two or more contiguous myocardial segments, microbubble contrast agents should be used to opacify the left ventricular cavity (LVC) and more effectively trace the tissue-blood interface. For this, some adjustments to image acquisition are necessary to prevent microbubbles from being destroyed prematurely and to help microbubbles remain stable. For LVC purposes, a very low mechanical index (< 0.2) is recommended, with harmonic activation using the pulse inversion technique. Most of the most recent echocardiography devices already have presets adjusted for this acquisition modality.[3,8]

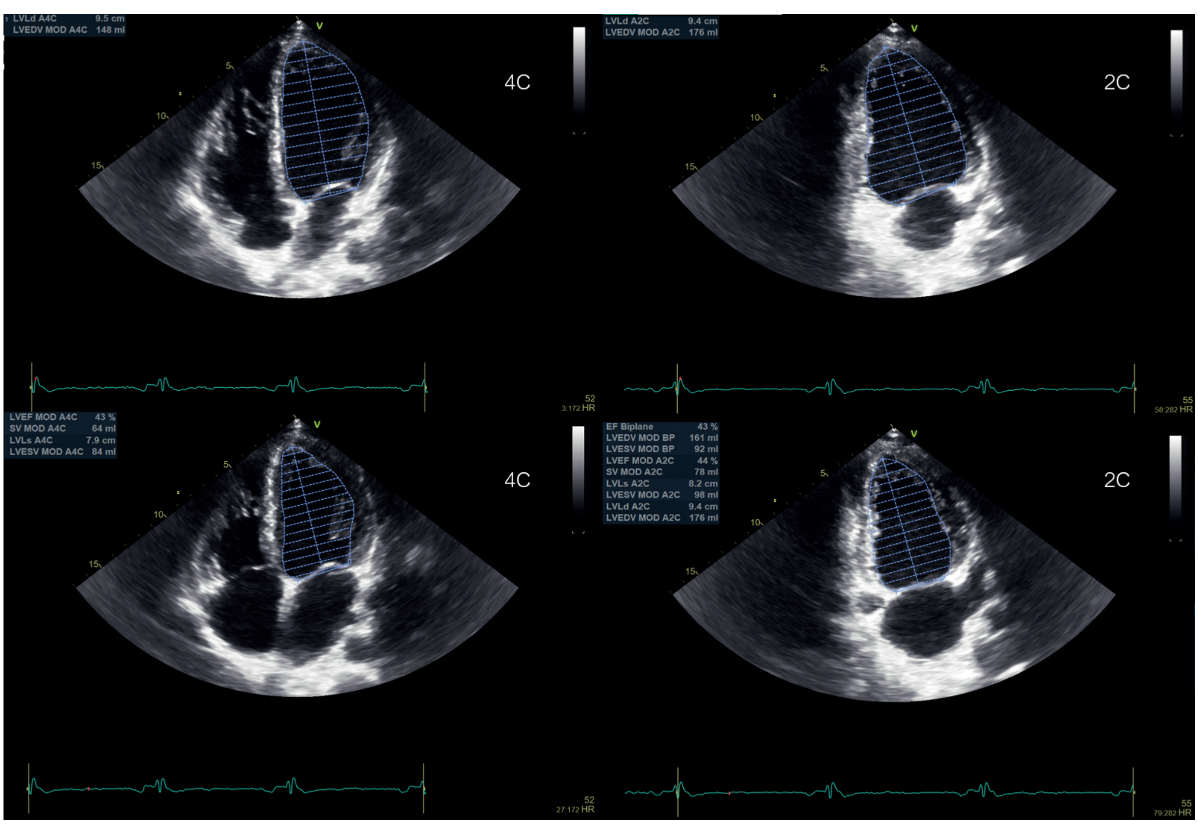


Figure 1 – *Measurement of left ventricular end-diastolic and end-systolic volumes using the biplane disc summation technique.*

Table 1 – Normal values for the global population of the WASE study by gender and compared with the 2015 ASE/EACVI

Variable	WASE, LLN to ULN			Guidelines	
	Male	Female	P	Male	Female
LVEDD, mm	36 to 56	33 to 51	<.0001	42 to 58	38 to 52
Indexed LVEDD, mm/m²	19 to 30	20 to 31	<.0001	22 to 30	23 to 31
LVESD, mm	22 to 37	21 to 34	<.0001	25 to 40	22 to 35
Indexed LVESD, mm/m²	12 to 20	12 to 21	<.0001	13 to 21	13 to 21
IVSd, mm	6 to 12	5 to 10	<.0001	6 to 10	6 to 9
PPd, mm	6 to 11	5 to 10	<.0001	6 to 10	6 to 9
LV mass, g	74 to 204	55 to 148	<.0001	88 to 224	67 to 162
Indexed LV mass, g/m²	42 to 101	36 to 85	<.0001	49 to 115	43 to 95
LVEDV, mL	61 to 65	47 to 122	<.0001	62 to 150	46 to 106
Indexed LVEDV, mL/m²	34 to 80	31 to 70	<.0001	34 to 74	29 to 61
LVESV, mL	21 to 65	17 to 47	<.0001	21 to 61	14 to 42
Indexed LVESV, mL/m²	12 to 32	11 to 28	<.0001	11 to 31	8 to 24
LVEF, %	57 to 68	58 to 69	<.0001	52 to 72	54 to 74
LV GLS, %	-17 to -24	-18 to -26	<.0001	NTo	NTo

LVEDD: left ventricular end-diastolic diameter; LVESD: left ventricular end-systolic diameter; IVSd: interventricular septal diastolic diameter; PPd: posterior wall diastolic diameter; LV: left ventricle; LVEDV: left ventricular end-diastolic volume; LVESV: left ventricular end-systolic volume; LVEF: left ventricular ejection fraction; GLS: global longitudinal strain; WASE: World Alliance Societies of Echocardiography; LLN: lower limit of normality; ULN: upper limit of normality.

Measurements of left ventricular volumes must follow the same recommendations described previously in this document, using the rule for the sum of biplane discs. The advantage of using ARUS is a more effective tracing of the endocardial borders, enabling more accurate measurement of end-diastolic and end-systolic volumes, the detection of thrombi within the left ventricular cavity, and accurate detailing of trabeculations and false tendons. Its disadvantages include the same limitations previously described for the biplane modified Simpson's rule and acoustic shadowing in the basal segments of the LV when using excess contrast agent (Video 2).[2,5,8]

The use of ARUS allows the measurement of LV volumes with less underestimation when compared to conventional 2D echocardiography, making it possible to estimate volumes with values closer to those obtained with magnetic resonance imaging.[2,3,8]

3D Echocardiography

3D echocardiography has evolved substantially in the 21st century after the emergence of second-generation full-matrix transducers. Although there are still limitations in terms of temporal resolution of the image, the gain in spatial resolution and the use of devices, such as multi-beat acquisition, make this echocardiographic modality the choice for measuring ventricular volumes and ejection fraction. Also, 3D echocardiography is not based on any geometric assumptions and eliminates the shortening bias of the LV apical region.[9,12,13] In the last decade, with software based on artificial intelligence mathematical algorithms, the time for acquiring 3D blocks and adjusting the images after processing has been significantly reduced, facilitating its routine use in the largest echocardiography centers in the world. Recent studies encourage the use of 3D echocardiography with artificial intelligence for analyzing left ventricular systolic function, which has been shown to be a quick, easy, reproducible, and feasible technique. It is possible to acquire left ventricular volume, stroke volume, and ejection fraction values that are very close to those estimated by the nuclear magnetic resonance imaging, considered as the gold standard technique.[5,10]

In conventional 3D echocardiography software, a 3D block should be initially acquired in full-volume acquisition mode, ideally in a layout that demonstrates the orthogonal sections of the block. Also, the entire LV should be centered in the image and inserted inside the 3D block. If the LV is not fully enclosed, the lateral size and elevation width of the block can be adjusted so that the entire LV is included. With an electrocardiogram exam, which must present a signal with clear identification of the P wave, QRS complex, and T wave, and ideally with the patient in a regular rhythm, the multi-beat feature is activated to merge smaller 3D blocks to obtain a 3D block in full-volume acquisition mode with a temporal resolution given by a volume rate greater than 20 Hz. Typically, this can be done safely using a multi-beat acquisition mode starting at four beats. In addition to an electrocardiogram with a good and stable signal, during image acquisition, the patient should hold their breath for the time proportional to the number of beats selected. They should not move so that no linear fusion artifacts are formed between the small blocks, known as stitch artifacts, which can compromise the analysis of the full-volume block that has been acquired (Video 3).[9]

After the acquisition described above, dedicated 3D software is used to analyze the LV, which may vary according to the equipment brand used. In general, these software solutions initially require confirmation of the exact moment of end-diastole, which has already been previously detected by recognizing the peak of the R wave on the electrocardiogram. After confirming the frame corresponding to this phase of the cardiac cycle, the coronal, sagittal, and transverse planes are aligned. The points corresponding to the ventricular basal endocardium are marked next to the mitral annulus and the LV apex in the coronal and sagittal planes. From there, the software will automatically recognize the compact blood-myocardium interface, with any necessary adjustments being immediately possible after this phase. As in 2D echocardiography, the trabeculae, papillary muscles, and any existing intracavitary thrombi must be included in the volumetric analysis. Subsequently, the software will request confirmation of the exact moment of the end of the systole, which has already been automatically detected by recognizing the end of the T wave on the electrocardiogram. After confirming the condition corresponding to this phase of the cardiac cycle, as well as in the end-diastole, the points corresponding to the ventricular basal endocardium next to the mitral annulus and the LV apex in the coronal and sagittal planes are marked. The software will also automatically recognize the endocardial borders, with the necessary adjustments being immediately possible after these phases.[9]

Based on a sequential analysis of the endocardial borders volume by volume over time, the software measures not only the end-diastolic and end-systolic volumes but also estimates the volumetric measurements throughout the cardiac cycle, creating a volume-time curve for the LV. It is also possible to segment the LV into 17 small, color-coded volumes and determine the volume-time curve for the regional volume of each of these segments, thus evaluating left intraventricular synchrony using the 3D technique.[9,11]

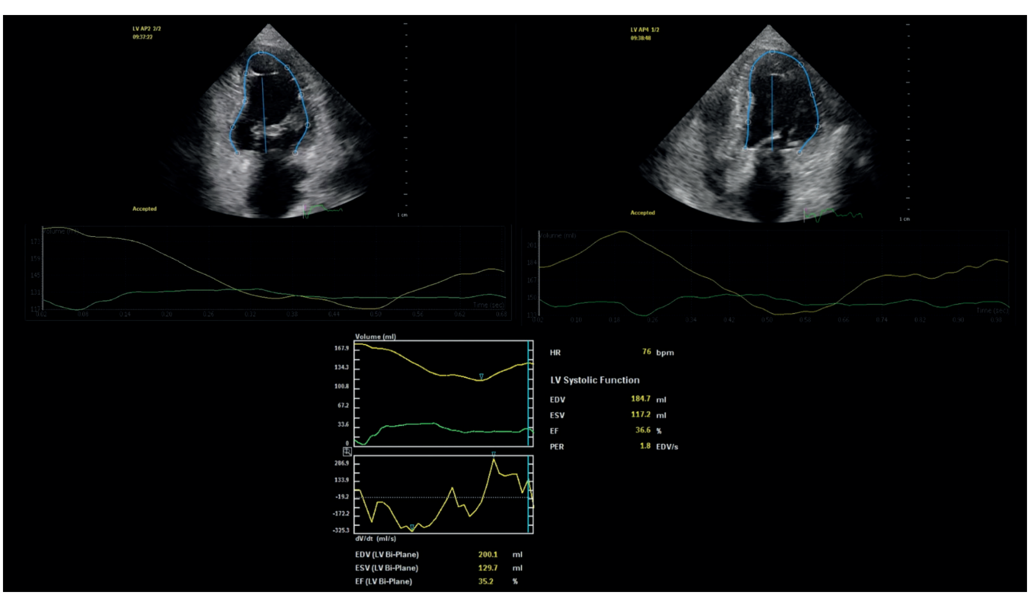
At the end of the analysis, the software will provide relevant 3D data on the LV's volumes and systolic function, such as end-diastolic and end-systolic volumes, stroke volume, ejection fraction, and the absolute and percentage systolic dyssynchrony index from the standard deviation of the time to peak corresponding to the lowest regional volume (time-to-peak) of 16 segments evaluated (Video 4).[9,11]

With the development of artificial intelligence software based on mathematical algorithms (MBA), it is possible to substantially reduce the acquisition time, post-processing adjustments, and analysis of the results found. It is also possible to measure the same data and even additional data on left ventricular systolic function obtained by conventional software with values very close to those obtained by nuclear magnetic resonance imaging.[5,10]

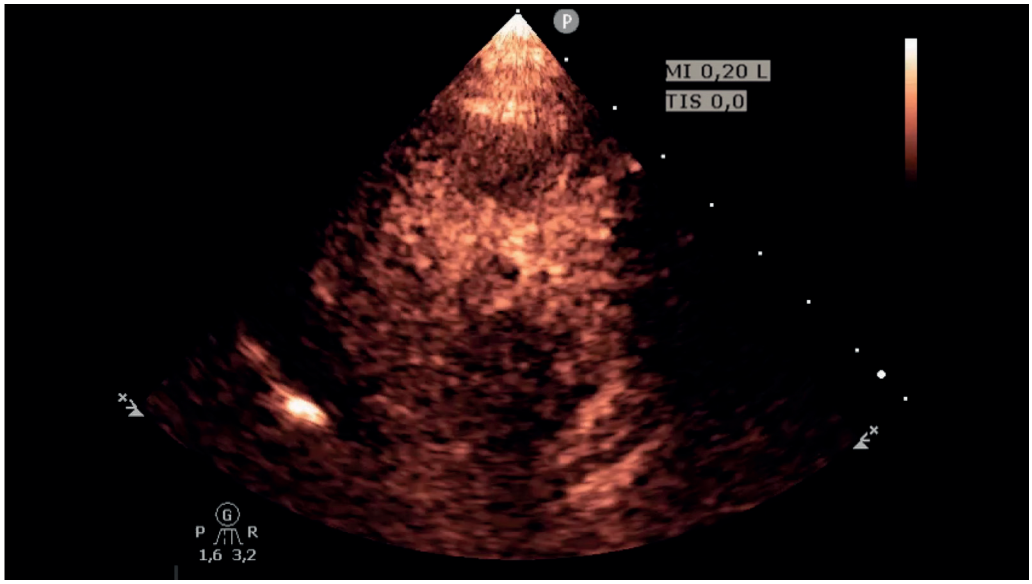
A full-volume 3D block must be acquired in a specific acquisition mode to be analyzed by artificial intelligence, with adjustments to the elevation width and lateral size so that the image volume rate is greater than 20 Hz. In this acquisition mode, care must be taken to ensure that not only the entire LV is included but also the left atrium (LA) because this type of software also analyzes the volume of the LA and its function. After recording the block, it must be evaluated using specific MBA software, which automatically recognizes the endocardial borders at the end of diastole, the end of systole, and throughout the cardiac cycle.[5,10]

After the analysis, which lasts 30 seconds on average, the software provides left ventricular data such as end-diastolic volume, end-systolic volume, volume-time curve, stroke volume, end-diastolic and end-systolic cavity lengths, cardiac output, index cardiac, and left ventricular mass. The latter can be calculated because this software also automatically recognizes the epicardial border. The software also allows detailed data to be obtained regarding left atrial function, such as maximum and minimum volumes, volume-time curve, and atrial emptying fraction. Furthermore, the trace of the endocardial and epicardial borders can be easily adjusted using apical views of 4C, 2C, and 3C, derived from the 3D block acquired both in end-diastole and end-systole (Video 5).[5,10]

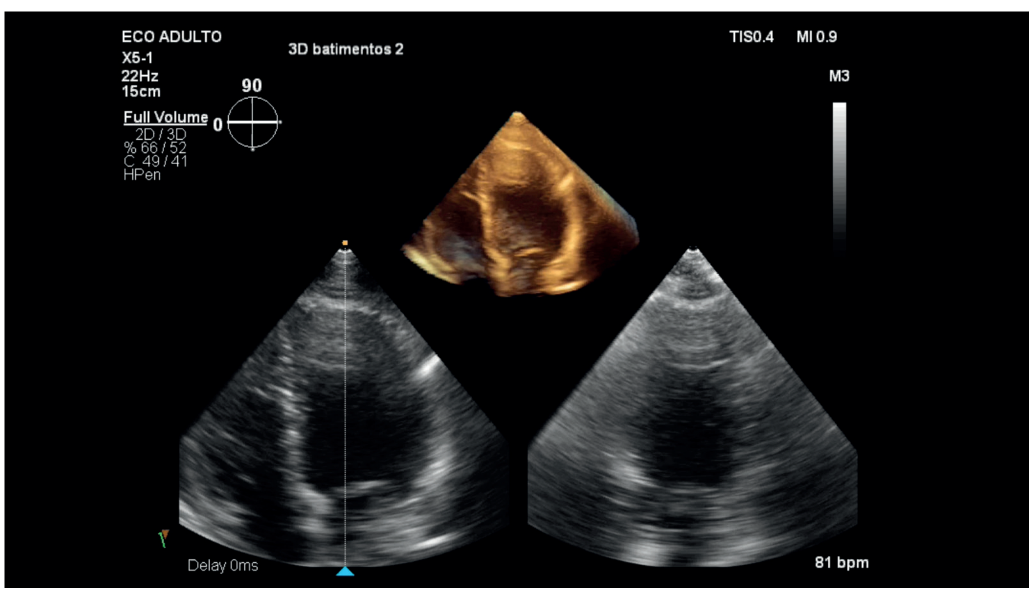
Normal values for the main 3D LV data are already well studied in the literature, such as in the NORRY study (Normal Reference Ranges for Echocardiography) with values described in the Table 2.[4]



Video 1 – *Estimation of LV volumes and ejection fraction by semi-automated software. Link: http://abcimaging.org/supplementary-material/2024/3703/2024-0059_AR_video-01.mp4.*



Video 2 – *The use of ARUS that detects the presence of a small thrombus at the apex of the LV in a patient with a suboptimal echocardiographic window. Link: http://abcimaging.org/supplementary-material/2024/3703/2024-0059_AR_video-02.mp4.*

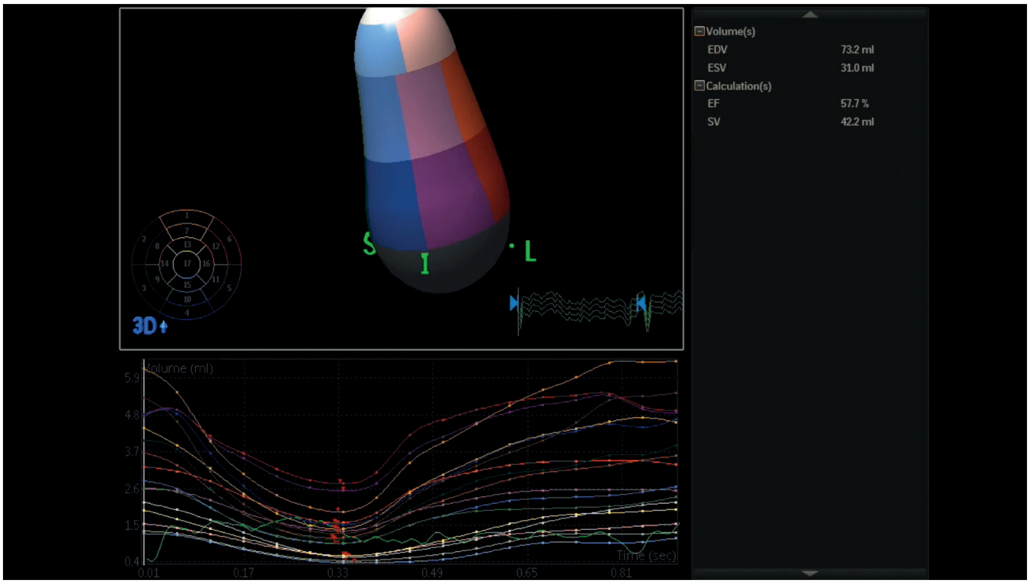


Video 3 – *Multi-beat full-volume 3D acquisition mode for analyzing LV volumes and ejection fraction. Link: http://abcimaging.org/supplementary-material/2024/3703/2024-0059_AR_video-03.mp4.*

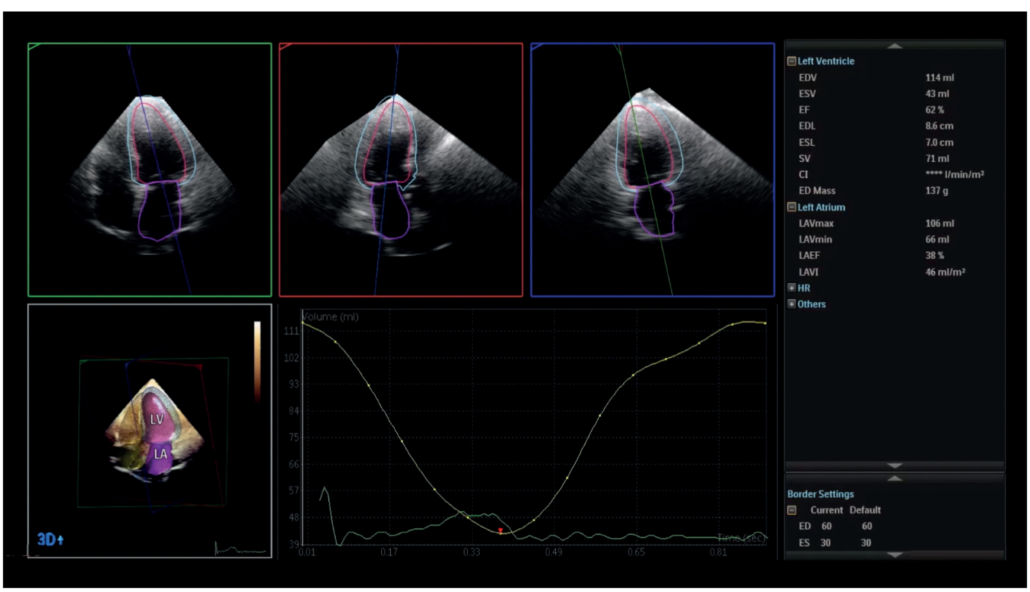
Thus, with the evolution of fully matrix 3D transducers and MBA software, it is currently possible to measure data far beyond the left ventricular ejection fraction in a quick, practical, reproducible way and with values that are very close to those obtained with the gold-standard technique of nuclear magnetic resonance imaging.[5,10]

Final considerations

Echocardiography is the most widespread diagnostic tool used to estimate the systolic function of the LV. It measures parameters such as ventricular volumes, stroke volume, and ejection fraction in a quick, noninvasive way without the use of radiation, iodinated contrast or gadolinium. Being an expert in



Video 4 – *3D analysis of LV volumes and ejection fraction using conventional software. Link: http://abcimaging.org/supplementary-material/2024/3703/2024-0059_AR_video-04.mp4.*



Video 5 – *3D analysis of the LV and LA in fully automated MBA software. Link: http://abcimaging.org/supplementary-material/2024/3703/2024-0059_AR_video-05.mp4.*

the technique is quite important to estimate these parameters accurately. Being able to refine the technique constantly is also important, and this is closely associated with the examiner's experience and knowledge of the current software solutions.

Methods such as ARUS and 3D echocardiography combined with the development of MBA software have greatly contributed to more accurate measurements, with low interobserver variability and results closer to those obtained by nuclear magnetic resonance imaging but with a much faster execution and analysis time. This is an extremely promising reality that is advancing substantially in major echocardiography centers around the world.

Table 2 – Ventricular volumes and systolic function indices by 3D analysis of the LV

Parameters	Total, Média ± DP	Intervalo interquartil LVEVD, mL	Homem, Média ± DP	Intervalo interquartil (25%–75%)	Mulher, Média ± DP	Intervalo interquartil (25%–75%)	P
LVESV, mL	115,6 ± 29,6	93,1–132,3	133,3 ± 30,5	114,2–150,2	102,5 ± 20,8	87,4–114,2	<0,001
LVEF, %	47,1 ± 13,7	36,6–55,3	55,4 ± 13,9	45,4–63,0	41,0 ± 9,9	33,6–48,5	<0,001
Stroke volume, mL	59,4 ± 4,6	55,9–62,5	58,5 ± 4,3	54,9–61,6	60,1 ± 4,6	56,7–63,2	<0,001
Indexed LVEDV, mL/m^2	68,5 ± 17,6	55,8–77,4	78,0 ± 18,6	63,7–92,2	61,5 ± 13,0	53,1–69,3	<0,001
Indexed LVESV, mL/m^2	63,9 ± 12,9	54,8–72,0	68,7 ± 14,0	58,6–77,2	60,4 ± 10,8	52,7–67,1	<0,001
Indexed stroke volume, mL/m^2	26,0 ± 6,2	21,3–29,7	28,5 ± 6,5	24,4–32,6	24,1 ± 5,3	20,4–27,5	<0,001
Longitudinal strain, %	37,9 ± 7,9	32,0–43,0	40,1 ± 8,7	34,1–46,5	36,3 ± 6,9	31,4–40,3	<0,001
Circumferential strain, %	-21,0 ± 2,6	-19,0 a 22,7	-20,4 ± 2,7	-18,6 a 22	-21,4 ± 2,4	-19,5 a 22,9	<0,001
Tangential strain, %	-30,3 ± 4,0	-27,4 a 33,0	-29,7 ± 3,9	-27,0 a 32,5	-30,7 ± 4,1	-27,6 a 33,3	0,012
Radial strain, %	-36,5 ± 3,9	-33,8 a 39,2	-36,0 ± 3,9	-33,2 a 38,9	-37,0 ± 3,8	-34,4 a 39,4	0,008
Strain radial, %	43,2 ± 4,5	40,0 a 46,2	42,1 ± 4,6	38,8 a 45,2	43,9 ± 4,3	40,7–46,7	<0,001

LVEDV: left ventricular end-diastolic volume; LVESV: left ventricular end-systolic volume; LVEF: left ventricular ejection fraction; SD: standard deviation.

Author Contributions

Writing of the manuscript: França LA; critical revision of the manuscript for intellectual content: França LA, Moleta DB.

Potential Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Study Association

This study is not associated with any thesis or dissertation work.

Ethics Approval and Consent to Participate

This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Feigenbaum H. Role of M-mode Technique in Today's Echocardiography. J Am Soc Echocardiogr. 2010;23(3):240-57. doi: 10.1016/j.echo.2010.01.015.
2. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L, et al. Recommendations for Cardiac Chamber Quantification by Echocardiography in Adults: An Update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. J Am Soc Echocardiogr. 2015;28(1):1-39. doi: 10.1016/j.echo.2014.10.003.
3. Porter TR, Mulvagh SL, Abdelmoneim SS, Becher H, Belcik JT, Bierig M, et al. Clinical Applications of Ultrasonic Enhancing Agents in Echocardiography: 2018 American Society of Echocardiography Guidelines Update. J Am Soc Echocardiogr. 2018;31(3):241-74. doi: 10.1016/j.echo.2017.11.013.
4. Bernard A, Addetia K, Dulgheru R, Caballero L, Sugimoto T, Akhaladze N, et al. 3D Echocardiographic Reference Ranges for Normal Left Ventricular Volumes and Strain: Results from the EACVI NORRE Study. Eur Heart J Cardiovasc Imaging. 2017;18(4):475-83. doi: 10.1093/ehjci/jew284.
5. Tamborini G, Piazzese C, Lang RM, Muratori M, Chiorino E, Mapelli M, et al. Feasibility and Accuracy of Automated Software for Transthoracic Three-Dimensional Left Ventricular Volume and Function Analysis: Comparisons with Two-Dimensional Echocardiography, Three-Dimensional Transthoracic Manual Method, and Cardiac Magnetic Resonance Imaging. J Am Soc Echocardiogr. 2017;30(11):1049-58. doi: 10.1016/j.echo.2017.06.026.
6. Galderisi M, Cosyns B, Edvardsen T, Cardim N, Delgado V, Di Salvo G, et al. Standardization of Adult Transthoracic Echocardiography Reporting in Agreement with Recent Chamber Quantification, Diastolic Function, and Heart Valve Disease Recommendations: An Expert Consensus Document of the European Association of Cardiovascular Imaging. Eur Heart J Cardiovasc Imaging. 2017;18(12):1301-10. doi: 10.1093/ehjci/jex244.
7. Bertrand PB, Levine RA, Isselbacher EM, Vandervoort PM. Fact or Artifact in Two-Dimensional Echocardiography: Avoiding Misdiagnosis and Missed Diagnosis. J Am Soc Echocardiogr. 2016;29(5):381-91. doi: 10.1016/j.echo.2016.01.009.
8. Mulvagh SL, Rakowski H, Vannan MA, Abdelmoneim SS, Becher H, Bierig SM, et al. American Society of Echocardiography Consensus Statement on the Clinical Applications of Ultrasonic Contrast Agents in Echocardiography. J Am Soc Echocardiogr. 2008;21(11):1179-201. doi: 10.1016/j.echo.2008.09.009.

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9. Lang RM, Badano LP, Tsang W, Adams DH, Agricola E, Buck T, et al. EAE/ASE Recommendations for Image Acquisition and Display Using Three-dimensional Echocardiography. J Am Soc Echocardiogr. 2012;25(1):3-46. doi: 10.1016/j.echo.2011.11.010.

10. Narang A, Mor-Avi V, Prado A, Volpato V, Prater D, Tamborini G, et al. Machine Learning Based Automated Dynamic Quantification of Left Heart Chamber Volumes. Eur Heart J Cardiovasc Imaging. 2019;20(5):541-9. doi: 10.1093/ehjci/jey137.

11. Kleijn SA, Aly MF, Knol DL, Terwee CB, Jansma EP, Abd El-Hady YA, et al. A meta-analysis of Left Ventricular Dyssynchrony Assessment and Prediction of Response to Cardiac Resynchronization Therapy by Three-dimensional Echocardiography. Eur Heart J Cardiovasc Imaging. 2012;13(9):763-75. doi: 10.1093/ehjci/jes041.

12. Jacobs LD, Salgo IS, Goonewardena S, Weinert L, Coon P, Bardo D, et al. Rapid Online Quantification of Left Ventricular Volume from Real-time Three-dimensional Echocardiographic Data. Eur Heart J. 2006;27(4):460-8. doi: 10.1093/eurheartj/ehi666.

13. Dorosz JL, Lezotte DC, Weitzenkamp DA, Allen LA, Salcedo EE. Performance of 3-dimensional Echocardiography in Measuring Left Ventricular Volumes and Ejection Fraction: A Systematic Review and Meta-analysis. J Am Coll Cardiol. 2012;59(20):1799-808. doi: 10.1016/j.jacc.2012.01.037.

14. Asch FM, Miyoshi T, Addetia K, Citro R, Daimon M, Desale S, et al. Similarities and Differences in Left Ventricular Size and Function among Races and Nationalities: Results of the World Alliance Societies of Echocardiography Normal Values Study. J Am Soc Echocardiogr. 2019;32(11):1396-406. doi: 10.1016/j.echo.2019.08.012.