pISSN 1975-4612/ eISSN 2005-9655

www.kse-jcu.org
https://doi.org/10.4250/jcu.2016.24.4.257
REVIEW J Cardiovasc Ultrasound 2016;24(4):257-267

Multimodality Imaging for Left Ventricular Hypertrophy Severity Grading: A Methodological Review

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Left ventricular hypertrophy (LVH), defined by an increase in left ventricular mass (LVM), is a common cardiac finding generally caused by an increase in pressure or volume load. Assessing severity of LVH is of great clinical value in terms of prognosis and treatment choices, as LVH severity grades correlate with the risk for presenting cardiovascular events. The three main cardiac parameters for the assessment of LVH are wall thickness, LVM, and LV geometry. Echocardiography, with large availability and low cost, is the technique of choice for their assessment. Consequently, reference values for LVH severity in clinical guidelines are based on this technique. However, cardiac magnetic resonance (CMR) and computed tomography (CT) are increasingly used in clinical practice, providing excellent image quality. Nevertheless, there is no extensive data to support reference values based on these techniques, while comparative studies between the three techniques show different results in wall thickness and LVM measurements. In this paper, we provide an overview of the different methodologies used to assess LVH severity with echocardiography, CMR and CT. We argue that establishing reference values per imaging modality, and possibly indexed to body surface area and classified per gender, ethnicity and age-group, might be essential for the correct classification of LVH severity.

KEY WORDS: Hypertrophy, left ventricular · Echocardiography · Magnetic resonance imaging · Multidetector computed tomography.

Introduction

Left ventricular hypertrophy (LVH), defined by an increase in left ventricular mass (LVM), is a common cardiac disorder with an estimated echocardiographic prevalence of 36–41% in patients with hypertension, which increases with age, hypertension severity and obesity.[1–3] LVH can be caused by an adaptation of the myocardium to increased pressure or volume load, genetic mutations or systemic conditions, as summarized in Table 1.[3–16] LVH develops gradually, and therefore patients remain asymptomatic in early stages. When the condition progresses, symptoms related to diastolic and systolic dysfunction ultimately bring the patient to the clinic.[6] Analysing the grade of LVH severity is of great importance to clinical practice in terms of prognosis and treatment choices. An increased LVM is strongly linked to an increased risk of cardiovascular events.[2)17)] The three main non-invasive cardiac imaging techniques used to assess the severity of LVH are echocardiography, cardiac magnetic resonance (CMR) and computed tomography (CT).[18)] With this manuscript, we provide a comprehensive methodological review of different techniques for the assessment of symmetrical LVH based on the following parameters: wall thickness, LVM and left ventricle (LV) geometry. Furthermore, we provide a simplified proposal for inter-technique standardization. We aim to summarize LVH reference values, indexed by body surface area (BSA) and classified per gender for optimal classification of LVH severity using different imag-

• Received: September 3, 2016 • Revised: October 28, 2016 • Accepted: November 30, 2016
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ing modalities.

PROS AND CONS OF IMAGING MODALITIES FOR ASSESSING LVH SEVERITY

ECHOCARDIOGRAPHY

Echocardiography was introduced in the 1950s and has become the cornerstone of non-invasive imaging of the heart. This currently widespread technique is based on ultrasound waves directed to the heart, which are reflected and translated into several modalities that can be used to assess LVH, namely: M-mode echocardiography; two-dimensional echocardiography (2DE), and three-dimensional echocardiography (3DE) images.[19)20)] The most important advantages of echocardiography are its wide accessibility, lack of radiation exposure, and excellent temporal resolution, which is superior to all other

Table 1. Overview of most important aetiologies of LVH

Summarized definition of aetiology	Rationale	Ref.
Obesity		
BMI ≥ 30 kg/m^2	A complex interplay of haemodynamic, metabolic and inflammatory changes have been associated with increased LVM	3)4)
Hypertension		
Systolic blood pressure > 140 mm Hg, or diastolic blood pressure > 90 mm Hg, and for patients with diabetes or chronic kidney disease: > 130 and/or > 80 mm Hg, respectively	Pressure overload leads to concentric hypertrophy	5)6)
Valvular heart disease		
Aortic stenosis		
Defined as severe with echocardiography when valve area < 1.0 cm^2, indexed valve area (cm^2/m^2 BSA) < 0.6, mean gradient > 40 mm Hg, and maximum jet velocity > 4.0 m/s for patients with normal cardiac output/transvalvular flow	Pressure overload leads to concentric hypertrophy	7)8)
Aortic regurgitation		
Quantitatively defined as severe with echocardiography when effective regurgitant orifice area ≥ 30 mm^2, or regurgitant volume ≥ 60 mL	Volume overload leads to eccentric hypertrophy	8)9)
Mitral regurgitation		
Quantitatively defined as severe with echocardiography when the effective regurgitant orifice area is ≥ 40 mm^2 in primary- and ≥ 20 mm^2 in secondary mitral regurgitation, and regurgitant volume is ≥ 60 and ≥ 30 mL, respectively	Volume overload leads to eccentric hypertrophy	8)10)
Genetic disorders		
Hypertrophic cardiomyopathy (most prevalent)		
In adults, wall thickness ≥ 15 mm in one or more LV myocardial segments—as measured by any imaging technique (echocardiography, CMR, or CT) that is not explained solely by loading conditions	Genetic mutations cause asymmetrical hypertrophy	11)
Other (genetic) disorders		
e.g., Anderson-Fabry, Pompe-, and Danon disease, cardiac amyloidosis, mitochondrial myopathy, mucopolysaccharidosis		
More than 40 types of other (genetic) disorders can cause LVH. Diagnostic plasma levels of disease-specific components, genetic testing, and echocardiography, mostly in family members of affected persons, are some of the techniques used to establish the diagnosis. LVH is often discovered later in life than other non-cardiac manifestations	Genetic mutations cause (among others) cardiac anomalies like hypertrophy, valvular- and systolic dysfunction	12–14)
Excessive physical exercise		
The definitions of 'excessive physical exercise' vary largely. As example we cite here Batterham et al.,[15)] who showed that training of > 10 hours per week for 10 weeks in healthy males was associated with an absolute increase in LVM of 4.8%	Excessive physical exercise that requires isometric muscle contraction can cause concentric hypertrophy, while exercises that require isotonic muscle contraction can cause eccentric hypertrophy	16)

LVH: left ventricular hypertrophy, BMI: body mass index, CMR: cardiac magnetic resonance, CT: computed tomography, LVM: left ventricular mass, LV: left ventricle

imaging techniques. M-mode echocardiography, often used for LVH assessment, has a temporal resolution up to 1 ms. However, echocardiography is operator and patient dependent, which could result in a relatively high inter-observer variability.[20–22] Furthermore, geometric assumptions represent an important limitation in LVM estimation in M-mode and 2DE, but this can be overcome by the use of 3DE: when 3DE measurements of LVM are compared to CMR measurements as gold standard, they correlate better, and have smaller limits of agreements, than LVM measurements with 2DE.[23][24] Although over-

Table 2. Comparison of imaging modalities used for LVH severity grading

Characteristics	M-mode echo	2D echo	3D echo	CMR	CT
Spatial resolution	++++	++++	++	+++	++++
Temporal resolution	++++	+++	+++	++	+
Radiation	-	-	-	-	+
Renal failure	-	-	-	+	+
Mechanical implants	-	-	-	+	-
Operator dependent	++	++	++	+	+
Low availability	-	-	-	++	+
Cost and resources	+	+	+	+++	++
Tissue characterization	-	-	-	+++	++
Geometric assumptions	++	++	-	-	-

LVH: left ventricular hypertrophy, echo: echocardiography, CMR: cardiac magnetic resonance, CT: computed tomography

Table 3. LV geometry and wall thickness cut-off values in guidelines and original studies for different imaging techniques

Imaging technique	LV geometry								Ref.	Ref. type
	Normal geometry		Concentric hypertrophy		Eccentric hypertrophy		Concentric remodeling			
	LVMi	RWT	LVMi	RWT	LVMi	RWT	LVMi	RWT		
2DE (men)	≤ 115	< 0.42	> 115	> 0.42	> 115	< 0.42	≤ 115	> 0.42	18)*	GL
2DE (women)	≤ 95	< 0.42	> 95	> 0.42	> 95	< 0.42	≤ 95	> 0.42	18)*	GL
CMR (not specified to gender)	68 ± 11	0.38 ± 0.04	95 ± 16	0.51 ± 0.06	83 ± 10	0.38 ± 0.04	72 ± 8	0.5 ± 0.04	34)†	OR
Imaging technique	Men				Women				Ref.	Ref. type
	Normal geometry		LV hypertrophy		Normal geometry		LV hypertrophy			
CT (available for LVMi, in different classification)	< 103		≥ 103		< 89		≥ 89		35)‡	OR
Imaging technique	Wall thickness								Ref.	Ref. type
	Men				Women					
	Normal range	Mildly abnormal	Moderately abnormal	Severely abnormal	Normal range	Mildly abnormal	Moderately abnormal	Severely abnormal		
Septal wall thickness: range (mm), UL or ± SD										
2DE	6–10	11–13	14–16	> 16	6–9	10–12	13–15	> 15	18)	GL
CMR	10.1; UL 11.7	-	-	-	8.9; UL 10.1	-	-	-	36)	OR
CT	9 ± 2	-	-	-	8 ± 1	-	-	-	37)	OR
Posterior wall thickness: range (mm), UL or ± SD										
2DE	6–10	11–13	14–16	> 16	6–9	10–12	13–15	> 15	18)	GL
CMR	9.9; UL 11.2	-	-	-	8.7; UL 9.8	-	-	-	36)	OR
CT	9 ± 2	-	-	-	8 ± 2		-	-	37)	OR

*RWT = (2 × posterior wall thickness / LV internal diameter at end diastole). LVMi = [(myocardial end-diastolic volume × myocardial density) / body surface area], †RWT = [(inferolateral + septal wall thickness at end-diastole) / LV end-diastolic diameter]. LVMi = as guidelines. Increased RWT was defined as > 0.45 mm, increased LVMi as > 81 g/m^2 (men) or > 62 g/m^2 (women), ‡LVMi: as guidelines. Criteria for abnormal LVM: above the 97th percentile for LVMi. 2DE: two-dimensional echocardiography, CMR: cardiac magnetic resonance, CT: computed tomography, GL: guidelines, LV: left ventricle, LVMi: left ventricle mass index, OR: original research, RWT: relative wall thickness (mm), SD: standard deviation, UL: upper limit, -: not available

estimation used to be a problem in 3DE LVM measurements, Shimada and Shiota[25] showed that accuracy of 3DE in LVM measurement has significantly increased over time, which was recently confirmed by Mizukoshi et al.,[26] who showed an excellent accuracy, correlation and agreement between 3DE and CMR LVM measurements.

In most patients, transthoracic echocardiography allows for an adequate assessment of the heart. Nevertheless, poor endocardial delineation due to insufficient image quality such as in patients with emphysema could be solved by using either transoesophageal approach or the use of contrast media.[18,21]

CARDIAC MAGNETIC RESONANCE

CMR became available in the beginning of the 1980's[27] and uses the nuclear magnetic resonance of hydrogen to identify specific tissues.[28] Characteristically, it is not dependent on acous-

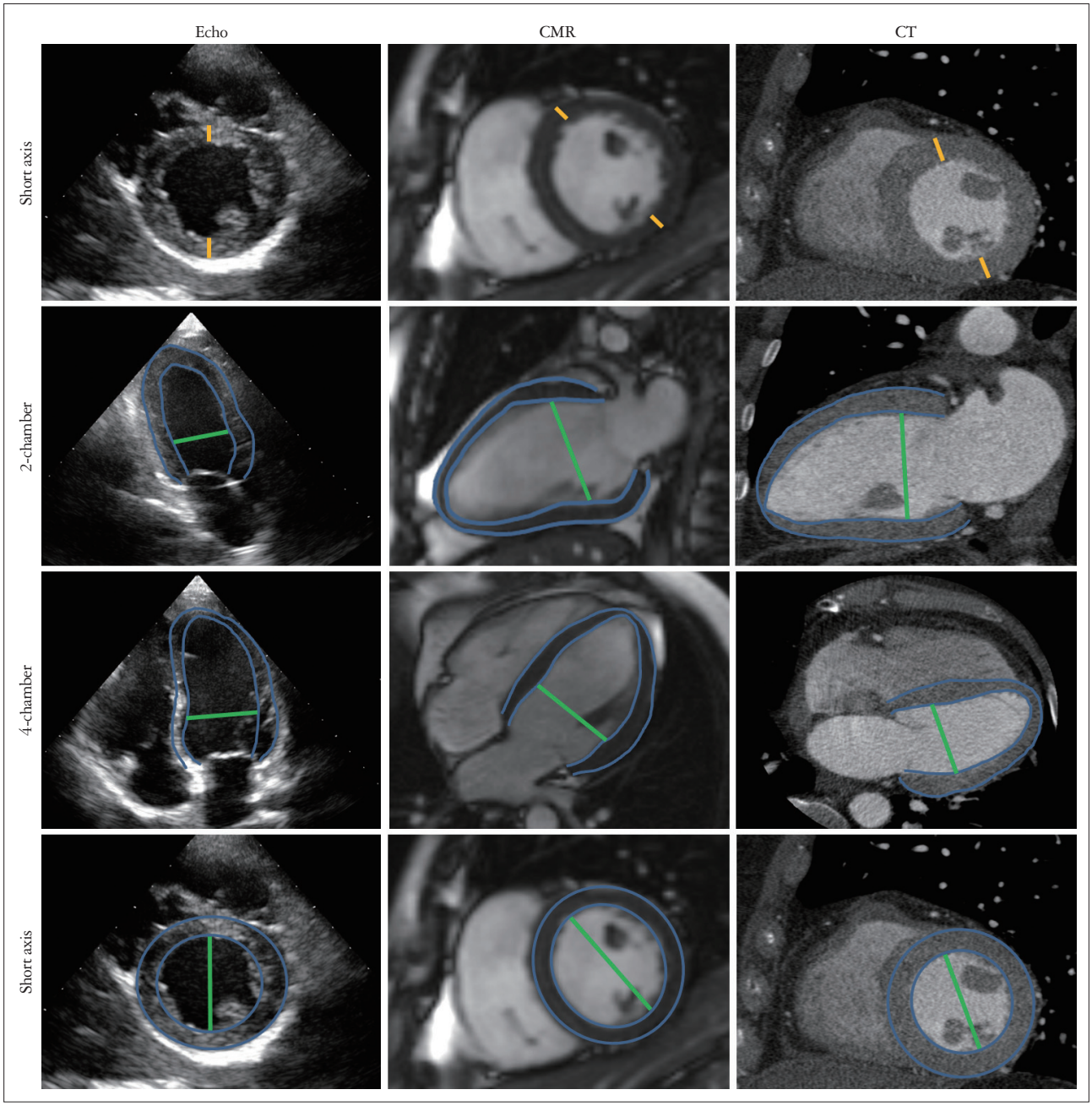

Fig. 1. Methodology for the measurement of the septal and posterior wall thickness, LV mass, and LV diastolic diameter with echo, CMR and CT. Short axis: measurements of septal and posterior wall thickness (yellow lines). 2-chamber, 4-chamber, and short axis views: contour drawing of the LV for three-dimensional LVM measurement (blue lines). Contour drawing may primarily be performed in short axis images (all available) and confirmed with long axis views; or, using primarily long axis views while rotating the LV on its longitudinal axis, and confirmed with short axis views (all available). LV (end-)diastolic diameter (green lines). Echo: echocardiography, CT: computed tomography, CMR: cardiac magnetic resonance, LV: left ventricle, LVM: left ventricular mass.

tic windows, measurements are less operator dependent, and overall resolution is adequate.[21)22)] This technique is considered the gold standard for assessment of most cardiac parameters including LVM, also allowing for cardiac tissue characterization. Notwithstanding, due to its high costs and lower availability, it is far less utilized than echocardiography.[21)22)] Furthermore, CMR has a relatively low spatial resolution (compared with CT), prolonged examination time, and is relatively contraindicated in patients with mechanical devices (e.g., pacemakers, prosthetic valves).[21)22)]

Computed tomography

CT utilizes X-rays that are sent through the body and absorbed at different intensities depending on the tissue. Detectors on the other side of the body identify the remaining X-rays, which allows for tissue differentiation.[29)] While the first CT scanners in the 1970's had only one detector and provided consequently a rather limited field of view per rotation, modern CT scanners have at least 64 detectors, and in the most advanced machines this number can reach even more than 700.[29)] The shift from electrocardiographic (ECG)-gated retrospective acquisitions towards ECG-triggered prospective acquisitions for the purpose of radiation dose reduction, limits the availability of end-diastolic phases, as preferably mid-diastolic phases are captured.[30)] Until now, no data is available regarding reference values for parameters such as wall thickness in mid-diastole. Cardiac CT is predominantly used for excluding the presence of coronary artery disease in patients with intermediate risk.[31)] However, the use of cardiac CT is expected to expand rapidly, since it allows for anatomical and functional evaluation of coronary lesions, and facilitates decision making before an invasive procedure.[32)33)] Furthermore, CT is used when a patient has contra-indications for CMR, offering an excellent spatial resolution and unrestricted field of view. However, the relatively low temporal resolution and the radiation exposure (ranging from 5–20 mSv[21)22)]) make cardiac CT the least preferred technique among the three for LVH assessment.[21)] Table 2 summarizes the main technically and clinically relevant characteristics of echocardiography, CMR and CT.

Methodology of LVH Assessment within Different Techniques

Guidelines with reference values for cardiac chamber quantification are available for echocardiography,[18)] but not yet for CT and CMR. Consequently, the reference values provided by these guidelines for echocardiography are used in the clinic for CMR and CT. The three main parameters for the assessment of LVH severity are wall thickness, LVM and LV geometry.[18)] Table 3 summarizes relevant parameters with cut-off values for LVH severity classification from the guidelines for echocardiography and available original reports for CMR and CT.[18)34-37)]

LV thickness

According to the guidelines for chamber quantification using echocardiography,[18)] LV posterior wall thickness is an important indicator for LVH severity. LV posterior wall, together with the LV internal diameter is used to calculate the relative wall thickness (RWT) as RWT = 2 × posterior wall thickness / LV internal diameter at end diastole. On the other hand, septal wall thickness gives an indication of the presence and severity

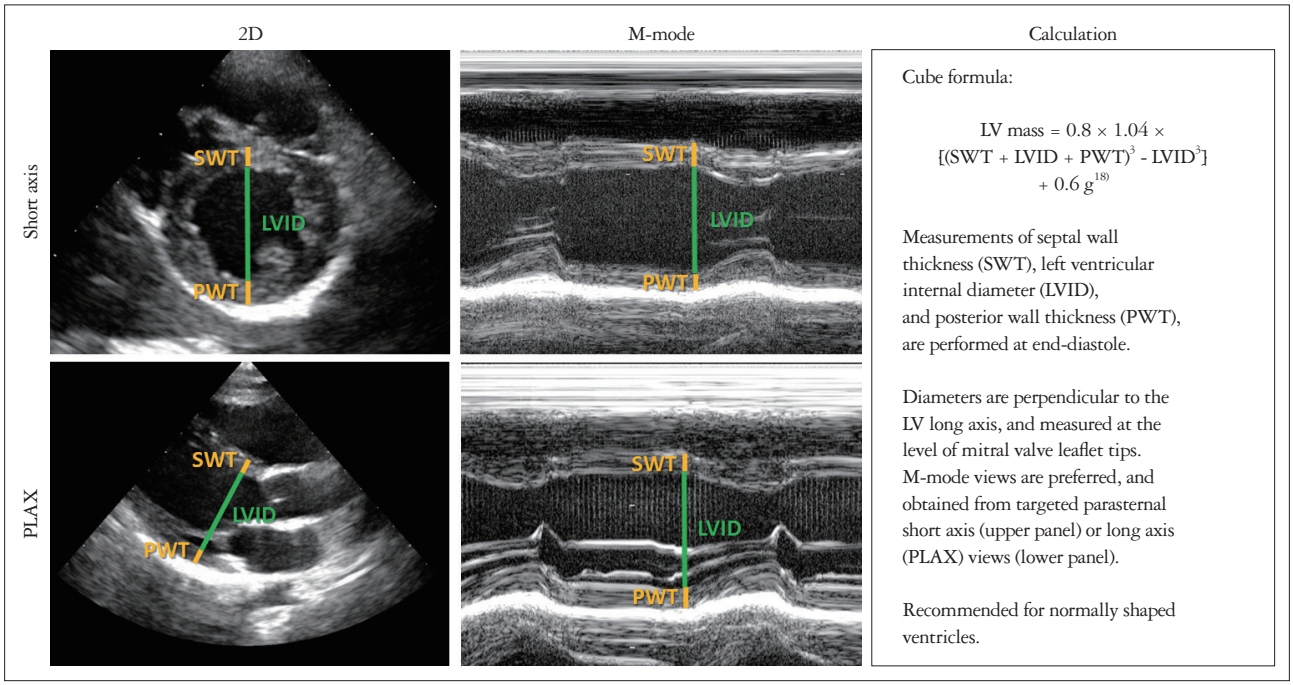

Fig. 2. Calculation of LV mass with an echocardiographic linear method. LV: left ventricle.

of LVH.[18] The latter parameter is often used in clinical practice.[38] In echocardiography, LV thickness quantitation is performed at end-diastole (the frame before mitral valve closure or the frame in the cardiac cycle in which the ventricular dimension or volume is the largest). Standard LV thickness measurements could be performed using either M-mode or 2D linear diameters.[18] The posterior wall is measured in the parasternal long-axis or short-axis view at or immediately below the level of the mitral valve leaflet tips, which is approximately at the junction of the basal- and mid-inferolateral segments (Fig. 1). Likewise, both views are used for the measurement of the septal wall, corresponding to the boundary between the basal- and mid-anteroseptal segments (Fig. 1).[18] In routine practice, although not formally recommended, septal thickness is often measured in the 4-chamber view, at the junction between the basal and mid inferoseptum, or simply at the level of the thickest portion. The appropriateness of this 2D measurement would require further validation. For CMR, the same reconstruction protocols based on 2D non-contiguous coverage of the LV or 3D whole-heart imaging, recreate those end-diastolic views used for echocardiography.[39] Thus, CMR linear measurements are obtained from the same segments as recommended for echocardiography. However, for CT, the views available for LVH assessment vary according to local reconstruction protocols. In principal, CT multiplanar reconstructions could reproduce the same segmentation used for echocardiography and CMR. Current software applications for CT- and CMR-based LV function and LVM assessment require contour delineation of the LV, and provide results of LV thickness using the 16-segment model, as well as LVM.[40]

LVM

LVM assessment with all three techniques requires quantification of myocardial end-diastolic volume which is calculated either through geometric formulas (when derived from M-mode or 2D images) or directly measured (in 3D imaging) (Fig. 1 and 2). After the end-diastolic myocardial volume is calculated, it is converted to mass by multiplying it with the myocardial density (approximately 1.05 g/mL).[18] To generate the LVM index (LVMi), the LVM is divided by BSA (resulting in the unit g/m^2).

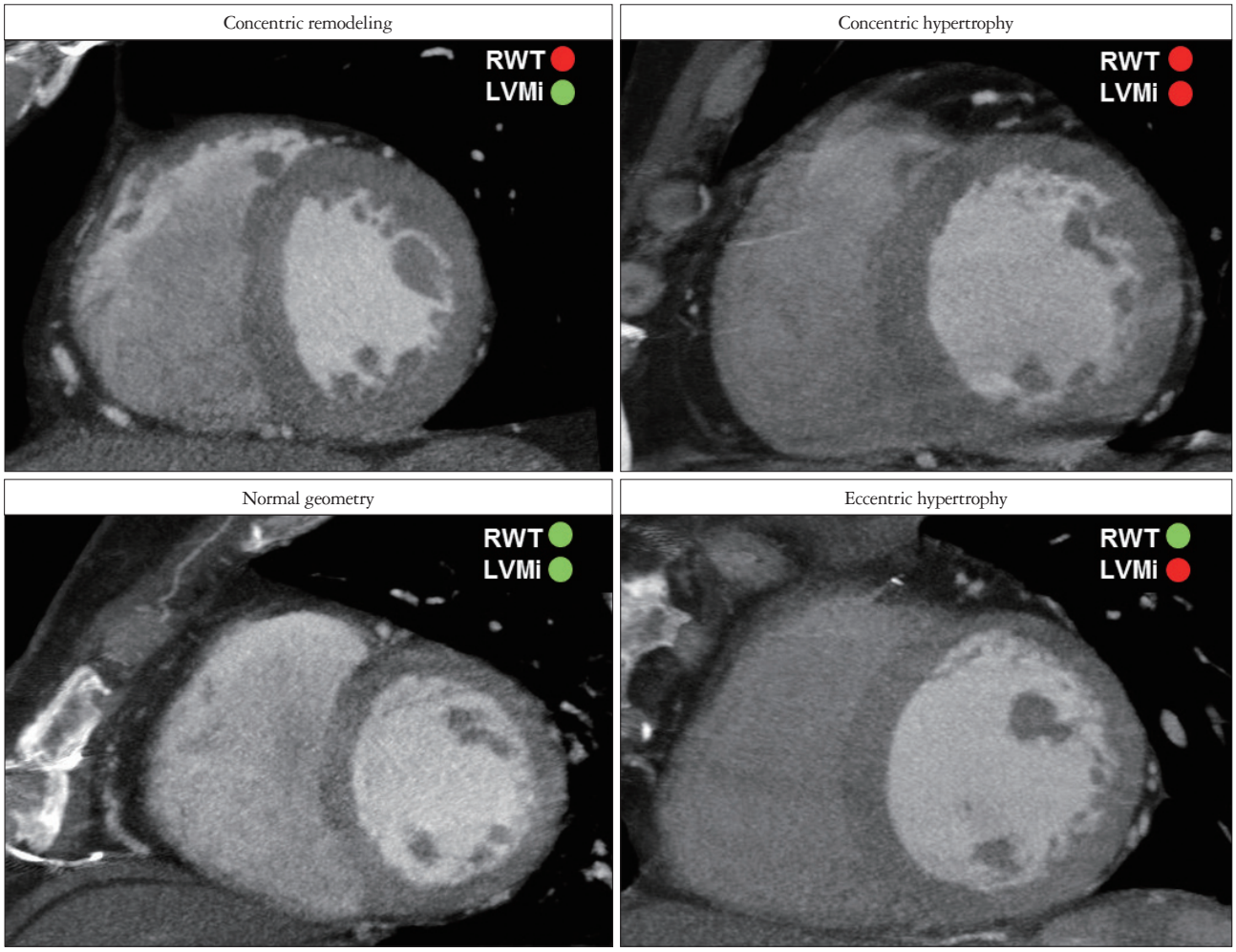

Fig. 3. LV geometry patterns. RWT = 2 × posterior wall thickness / LV internal diameter at end diastole. LVMi = LVM / BSA. Normal = green, abnormal = red. Abnormal RWT is defined as > 0.42, abnormal LVMi is > 115 g/m^2 (men), and > 95 g/m^2 (women).[18] RWT: relative wall thickness, LVMi: left ventricular mass index, LV: left ventricle, LVM: left ventricular mass, BSA: body surface area.

Table 4. Non-invasive imaging techniques compared in assessment of wall thickness

Techniques compared	Results ± SD or range		Parameter	Phase	Unit	n	Patient description	CC, (95% CI), *p*	BA bias, LOA or SD	Calculation BA	Ref.
2DE vs. 3DE	2DE	3DE									
	28.0 ± 8.1	27.7 ± 7.5	Segm. WT	ED/ES	mm	20	HCM	r = 0.92, (0.90–0.94), *p* < 0.001	Bias = 0.1, LOA = -5.8 to 6.1	3DE - 2DE	43)
CT vs. 2DE	64-slice CT	2DE									
	0.9 ± 0.2	1.1 ± 0.3	Sept. WT	ED	cm	100	Referred for CCTA	-	Bias = 0.20, *p* < 0.001, LOA = -0.20 to 0.60	2DE - CT	37)
	0.9 ± 0.2	1.0 ± 0.2	Post. WT	ED	cm	100	Referred for CCTA	-	Bias = 0.10, *p* < 0.001, LOA = -0.18 to 0.38	2DE - CT	37)
	8.83 (range 2.5–15.5)	11.03 (range 7–15)	Sept. WT	ED	mm	116	Referred for CCTA	r = 0.47, *p* = 0.001	Bias = -24.6%, LOA = -76.1 to 20.9%	CT - 2DE	44)
	9.67 (range 6–21)	9.7 (range 7–15)	Post. WT	ED	mm	116	Referred for CCTA	r = 0.243, *p* = 0.104	Bias = -7.4%, LOA = -55.4 to 40.5%	CT - 2DE	44)
	10 ± 1.4	11 ± 1.5	Sept. WT	ED	mm	25	Heart failure	r = 0.77, *p* = 0.50	-	-	45)
	10 ± 1.3	10 ± 1.4	Post. WT	ED	mm	25	Heart failure	r = 0.76, *p* = 0.68	-	-	45)
2DE vs. CMR	2DE	CMR									
	10 ± 3	10 ± 1	Sept. WT	ED	mm	44	Normal LV dimensions	r = 0.57, *p* < 0.05	Bias = 0.6, SD = 1.9	CMR - 2DE	46)
	9 ± 2	9 ± 1	Post. WT	ED	mm	44	Normal LV dimensions	r = 0.49, *p* < 0.05	Bias = 0.3, SD = 1.3	CMR - 2DE	46)
	28.0 ± 8.1	27.8 ± 8.0	Segm. WT	ED/ES	mm	20	HCM	r = 0.85 (0.82–0.88), *p* < 0.001	Bias = 0.4, LOA = -7.7 to 8.6	CMR - 2DE	43)
	21.7 ± 9.1	22.5 ± 9.6	Max LV WT	ED	mm	48	HCM	t-test, *p* = 0.21	-	-	47)
	13 ± 6	17± 8	BAL free wall	ED	mm	48	HCM	t-test, *p* = 0.001	-	-	47)
3DE vs. CMR	3DE	CMR									
	27.7 ± 7.5	27.8 ± 8.0	Segm. WT	ED/ES	mm	20	HCM	r = 0.90 (0.87–0.91), *p* = 0.001	Bias = 0.3, LOA = -6.6 to 7.2	CMR - 3DE	43)
CT vs. CMR	64-slice CT	CMR									
	-	-	Segm. WT	ED	mm	80	HCM	r = 0.88, *p* < 0.01	Bias = 0.61, LOA = -5.39 to 6.61	CMR - CT	48)
	21.9 ± 7.0	22.5 ± 6.6	Max WT	ED	mm	60	HCM	r = 0.96, *p* < 0.01	Bias = 0.5, LOA = -2.4 to 3.1	CMR - CT	49)
CT vs. CMR	16-slice CT	CMR									
	9.8 ± 3.6	10.0 ± 3.5	Segm. WT	ED	mm	19	Various heart diseases	r = 0.89, *p* < 0.05	Bias= -, LOA = -3.65 to 3.15	CMR - CT	50)
	13.8 ± 4.4	14.1 ± 4.3	Segm. WT	ES	mm	19	Various heart diseases	r = 0.85, *p* < 0.05	Bias= -, LOA = -5.06 to 4.54	CMR - CT	50)
	-	-	Segm. WT	ED	mm	30	Various heart diseases	-	Bias = -0.54, SD = 2.19	CMR - CT	51)

2/3DE: two/three-dimensional echocardiography, BA: Bland-Altman analysis, BAL: basal anterolateral, CC: correlation coefficient, cm: centimetre, CT: computed tomography, CCTA: cardiac CT angiography, CI: confidence interval, CMR: cardiac magnetic resonance, ED: end-diastole, ES: end-systole, HCM: hypertrophic cardiomyopathy, LV: left ventricle, LOA: limits of agreement, Post.: posterior, r: Pearson correlation coefficient, SD: standard deviation, Segm.: segmental, Sept.: septal, WT: wall thickness, -: not available

LV GEOMETRY

Determination of the LV geometry according to guidelines requires the LVMi and RWT as described above.[6)18)] With regards to geometry, the LV can be described as normal, concentric remodelled, and concentric or eccentric hypertrophied, as depicted in Fig. 3 and Table 3. Other classifications have been suggested, possibly increasing the prognostic value of LVH based on dilatation.[41)42)] As this review focuses on methodology of guideline based assessment of LVH severity, we would like to point interested readers to references on this important topic.[41)42)]

INTER-TECHNIQUE AGREEMENT AND DISAGREEMENT

Although the methods for chamber quantitation may apply

Table 5. Non-invasive imaging techniques compared in assessment of left ventricular mass

Techniques compared	Results ± SD or range		Parameter	Unit	n	Patient description	CC, (95% CI), *p*	BA bias, LOA or SD or 95% CI	Calculation BA	Ref.
2DE vs. 3DE	2DE	3DE								
	219±81	193±65	LVM	g	112	Hypertension, aortic stenosis, and healthy	r = 0.85, *p* < 0.001	Bias = 26 ± 42, LOA = -58 to + 110	M-mode - 3DE	52)
CT vs. 2DE	64-Slice CT	2DE								
	119 ± 30	115 ± 38	LVM	g	100	Referred for CCTA	-	Bias = -4, t-test *p* = n.s.	2DE - CT	37)
	95.73	205.5	LVM	g	116	Referred for CCTA	r = 0.419, *p* = 0.006	Bias = -7.09, LOA = -151.5 to 9.6%	CT - 2DE	44)
Echo vs. CMR	2DE	CMR								
	178.2 ± 46.0	171.0 ± 52.4	LVM	g	35	LVH	r = 0.989	Bias = 7.20, LOA = -37 to 50	CMR - 2DE	53)
	194.4 ± 52.9	107 ± 24.4	LVMi	g/m^2	67	Heart failure and low EF	r = 0.45 (0.18–0.65), *p* = 0.002	Bias = -79.9, LOA = -173.4 to 13.5	CMR - 2DE	54)
	-	177 ± 56	LVM	g	25	Healthy and various heart conditions	r = 0.91	Bias = 15.9 ± 95% CI 54.9	CMR - 2DE	55)
Echo vs. CMR	3DE	CMR								
	248 ± 93	248 ± 93	LVM	g	20	HCM	r = 0.97, *p* < 0.001	Bias = -6.3, LOA = -54.7 to 42.2	CMR - 3DE	43)
	-	177 ± 56	LVM	g	25	Healthy and various heart conditions	r = 0.99	Bias = 1.2 ± 95% CI 12.7	CMR - 3DE	55)
CT vs. CMR	64-Slice CT	CMR								
	22.6 ± 12.7 (range, 7.3–45.0)	24.2 ± 13.0 (range, 9.3–47.1)	MDE mass	g	80	HCM	r = 0.97, *p* < 0.01	Bias = -1.26, LOA = -7.80–4.55	CMR - CT	48)
	136.2 ± 51.9	152.5 ± 57.8	LVM	g	36	Referred for CCTA	r = 0.93, *p* > 0.001	LOA = ± 42.0	CMR - CT	56)
	207.5 ± 88.1	210.6 ± 83.6	LVM	g	60	HCM	r = 0.95, *p* < 0.01	Bias = 3.1, LOA = -50.1 to 56.3	CMR - CT	49)

2/3DE: two/three-dimensional echocardiography, BA: Bland-Altman analysis, CC: correlation coefficient, CT: computed tomography, CCTA: cardiac CT angiography, CI: confidence interval, CMR: cardiac magnetic resonance, HCM: hypertrophic cardiomyopathy, LOA: limits of agreement, LV: left ventricle, LVH: LV hypertrophy, LVM: left ventricular mass, LVMi: left ventricular index, MDE: myocardial delayed enhancement, r: Pearson correlation coefficient, SD: standard deviation, -: not available, EF: ejection fraction

for all techniques, differences in spatial and temporal resolution can account for variations in reference values, as shown by comparative studies,[37)43-56)] of which the most important results are summarized in Table 4 and 5 for wall thickness and LVM, respectively. The comparative studies show that agreement is acceptable between techniques. When echocardiography is compared to CMR or CT in the measurement of wall thickness and LVM, generally a weaker Pearson's correlation and a larger bias with accompanying limits of agreement are found[37)43-47)53-55)] than when CMR and CT are compared,[48-51)56)] indicating that the most important drawback of echocardiography is the larger operator dependence, as compared to CMR and CT; most likely caused by the lower spatial resolution of echocardiography. Noteworthy, a difference of 2 mm in septal wall thickness could reclassify the presence and/or the severity of LVH (Table 3).[6)18)] Interestingly, although CMR is considered the gold standard for measurement of most cardiac parameters, CT is known to be the least operator dependent when it comes to measurements of for example the aorta and aortic annulus.[57)58)] The studies cited in Table 4 and 5, however, do not show a clear difference in operator dependence when CMR and CT are compared, indicating that for the parameters that are used for LVH severity assessment, both CMR and CT will suffice if the quality of echocardiographic measurements of parameters that are relevant for LVH severity assessment are not sufficient.

Gender, Ethnicity, Age, and Body Surface Area

Several studies have shown that gender, age, body size, and ethnicity influence reference values for cardiac parameters.[2)18)] Accordingly, reference values should be examined with caution. Indexing the LVM to BSA or height^x (where x stands for allometric powers such as 1.7, 2.13, or 2.7) allows for better comparison of persons with different body sizes. However, the optimal indexing method remains controversial. Most studies have used LVM/BSA, nevertheless recent data suggests that indexing LVM to height^x may more accurately predict events in obese patients.[18)] Paucity of data in this regard prompts the need for continued research in populations with normal and hypertrophied hearts.

Conclusion

LVH severity grading is important for diagnosis, prognosis and guidance of therapy. Three main parameters including wall thickness, left ventricular mass, and left ventricular geometry, are easily assessed with echocardiography, CT or CMR. Data representing normal populations is abundant for echocardiography, however still limited for CT or CMR. A standard methodology for LVH severity grading among modalities is advised to further improve comparability and facilitate clinical decision making.

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