Received: 13 May 2020 | Accepted: 2 February 2021

DOI: 10.1111/cpf.12693

ORIGINAL ARTICLE

Clinical Physiology and Functional Imaging

Atrioventricular plane displacement versus mitral and tricuspid annular plane systolic excursion: A comparison between cardiac magnetic resonance and M-mode echocardiography

Alvaro Sepúlveda-Martínez[1,2,3] | Katarina Steding-Ehrenborg[3,4] | Mérida Rodríguez-López[1,5,6] | Ellen Ostenfeld[3] | Brenda Valenzuela-Alcaráz[1] | Einar Heiberg[3,7] | Eduard Gratacós[1] | Susanna Prat-González[8] | Fátima Crispi[1] | Erik Hedström[3,9]

[1]BCNatal, Fetal Medicine Research Center (Hospital Clínic and Hospital Sant Joan de Déu, University of Barcelona, Barcelona, Spain

[2]Fetal Medicine Unit, Department of Obstetrics and Gynecology, Hospital Clínico Universidad de Chile, Santiago de Chile, Chile

[3]Clinical Physiology, Department of Clinical Sciences Lund, Lund University, Skane University Hospital, Lund, Sweden

[4]Department of Health Sciences, Physiotherapy, Lund University, Lund, Sweden

[5]Pontificia Universidad Javeriana Cali, Cali, Colombia

[6]Department of Biomedical Engineering, Faculty of Engineering, Lund University, Lund, Sweden

[7]Wallenberg Center for Molecular Medicine, Lund University, Lund, Sweden

[8]Cardiovascular Institute, Hospital Clínic, Institut d'Investigacions Biomèdiques August Pi i Sunyer (IDIBAPS, Barcelona, Spain

[9]Diagnostic Radiology, Department of Clinical Sciences Lund, Lund University, Skane University Hospital, Lund, Sweden

Correspondence
Erik Hedström, MD, PhD, Clinical Physiology, Department of Clinical Sciences Lund, Lund University, Lund, Sweden.
Email: erik.hedstrom@med.lu.se

Funding Information
This project has been funded with support of Erasmus Mundus, Heart-Lung Foundation, Region of Skane, Skane University Hospital Lund, Medical Faculty at Lund University, and the Knut and Alice Wallenberg foundation, the Instituto de Salud Carlos III (PI15/00130, PI14/00226, PI17/00675, INT16/00168) integrados en el Plan Nacional de I + D + I y cofinanciados por el ISCIII-Subdirección General de Evaluación y el Fondo Europeo de Desarrollo Regional (FEDER) 'Otra manera de hacer Europa' (Spain); Erasmus + Programme of the European Union (Framework Agreement number: 2013-0040) This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein; 'la Caixa' Foundation under agreement LCF/PR/

Abstract

Introduction: Both echocardiography and CMR imaging are used to quantify longitudinal function. Inter-method variability for mitral (MAPSE) and tricuspid (TAPSE) annular plane systolic excursion, and variability between directly measured MAPSE and TAPSE and as based on atrioventricular plane displacement (AVPD) analysis by CMR, are, however, not known. This study, therefore, assessed inter-method variability and variability between annular plane systolic excursion and AVPD-based values in a healthy adult population.

Methods: Echocardiography and CMR were performed in 111 adults (35 [32–38] years). Method comparisons were assessed with Deming regression, Bland–Altman analysis and coefficient of variation. Observer reproducibility was assessed by the concordance correlation coefficient.

Results: Echocardiography and semi-automatic CMR agreed on MAPSE (17 ± 2 mm vs. 17 ± 2 mm, $p = 0.1$) and TAPSE (25 ± 3 mm vs. 25 ± 3 mm, $p = 0.5$), correlated highly between methods (fitted-slope 1.22 [95% CI 1.07–1.38] and 1.12 [95% CI 0.95–1.29]) and showed low bias (0.42 [95% CI − 2.05 to 2.88] and − 0.18 [95% CI − 4.78 to 4.43]). Intra-/inter-observer reproducibility was high for both methods for both

GN14/10270005 (Spain); AGAUR 2014 SGR grant n° 928 and Cerebra Foundation for the Brain Injured Child (Carmarthen, Wales, UK). This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

MAPSE (echocardiography 0.96/0.86; CMR 0.87/0.85) and TAPSE (echocardiography 0.96/0.95; CMR 0.97/0.96). MAPSE (16 ± 2 mm vs. 17 ± 2 mm; $p < 0.001$) and TAPSE (24 ± 3 vs. 25 ± 3 mm; $p < 0.001$) based on AVPD were similar but statistically different compared with semi-automatic CMR.

Conclusions: Echocardiography and semi-automatic CMR have low variability and provide similar values for MAPSE and TAPSE and are thus interchangeable for follow-up studies. Lateral values based on tracked data from AVPD analysis are not clinically significantly different and could be used as a representation of annular displacement.

KEYWORDS

atrioventricular plane displacement, cardiac magnetic resonance, comparison, echocardiography, MAPSE, TAPSE

1 | INTRODUCTION

Ventricular systolic function is dependent on both longitudinal pumping, that is the base-to-apical movement of the valve plane, and radial pumping, that is the squeezing motion of the ventricle. Longitudinal pumping is the main contributor to stroke volume on both the left and right cardiac side (Carlsson et al., 2007a, 2007b; Steding-Ehrenborg et al., 2015). Measures of longitudinal function are of clinical importance as a decreased longitudinal function has prognostic implications (Romano et al., 2019). Mitral annular plane systolic excursion (MAPSE) and tricuspid annular plane systolic excursion (TAPSE) as measures of systolic longitudinal function can be assessed by echocardiography (Dutta & Aronow, 2017; Feigenbaum et al., 1967; Kaul et al., 1984; Medvedofsky et al., 2015). Further, cardiovascular magnetic resonance (CMR) can assess both MAPSE and TAPSE and the atrioventricular plane displacement (AVPD) (Seemann et al., 2017). Measurement points for AVPD are placed on the basal top of the compact myocardium in the respective long-axis. This may differ from where the mitral and tricuspid annuli and valve hinge points are visualized, and it may be hypothesized that MAPSE and TAPSE according to clinical routine and as based on tracked data from AVPD analysis may result in different values. Also, inter-method variability for MAPSE and TAPSE, and variability between MAPSE/TAPSE by echocardiography and based on AVPD by CMR are not known.

The aims of this study were therefore to compare MAPSE and TAPSE by echocardiography with values by semi-automatic CMR analysis from both direct measurements and based on tracked data from AVPD and to determine reproducibility of both methods in a healthy adult population.

2 | METHODS

2.1 | Study design

The Ethics Committee of Hospital Clinic and Hospital Sant Joan de Deu approved the study protocol, and the study was performed in accordance with the Helsinki Declaration. Healthy subjects between age 25 and 40 years were invited to participate and underwent a complete cardiovascular risk assessment. Exclusion criteria were cardiovascular or renal disease, diabetes mellitus, autoimmune disease or contraindications to CMR. All subjects provided written informed consent before participation and underwent comprehensive echocardiography and CMR studies.

2.2 | Echocardiography

All subjects were evaluated according to clinical routine in the left lateral decubitus position performed by an experienced cardiologist from the Cardiology Unit of Hospital Clínic, Barcelona, with more than ten years of clinical practice. A Vivid E9 ultrasound machine (GE Healthcare, Horten, Norway) with a 3.5 MHz (M5S) transducer was used for all examinations with image acquisition synchronized to ECG. Cine loops of the apical four-chamber view and M-mode images acquired in free breathing were stored for off-line analyses.

An experienced observer (A.S-M.) quantified MAPSE and TAPSE off-line using the software Echopac® (GE Healthcare, Milwaukee, WI, USA). In short, 2D-mode cines with frame rates of 60–70 frames per second were used. An M-mode line was applied across the lateral mitral and tricuspid annulus in the four-chamber view for assessment of MAPSE and TAPSE, respectively (Figure 1). Two to three echocardiography cine data sets were acquired in each patient, and the clip number was not known for the second observation.

2.3 | Cardiovascular magnetic resonance

Cardiovascular magnetic resonance imaging was performed using a 3T scanner (Magnetom Trio, Siemens Healthcare, Erlangen, Germany) applying a balanced steady-state free precession (bSSFP) cine sequence with retrospective ECG gating under end-expiratory breath hold. Standard long-axis cine images were acquired with

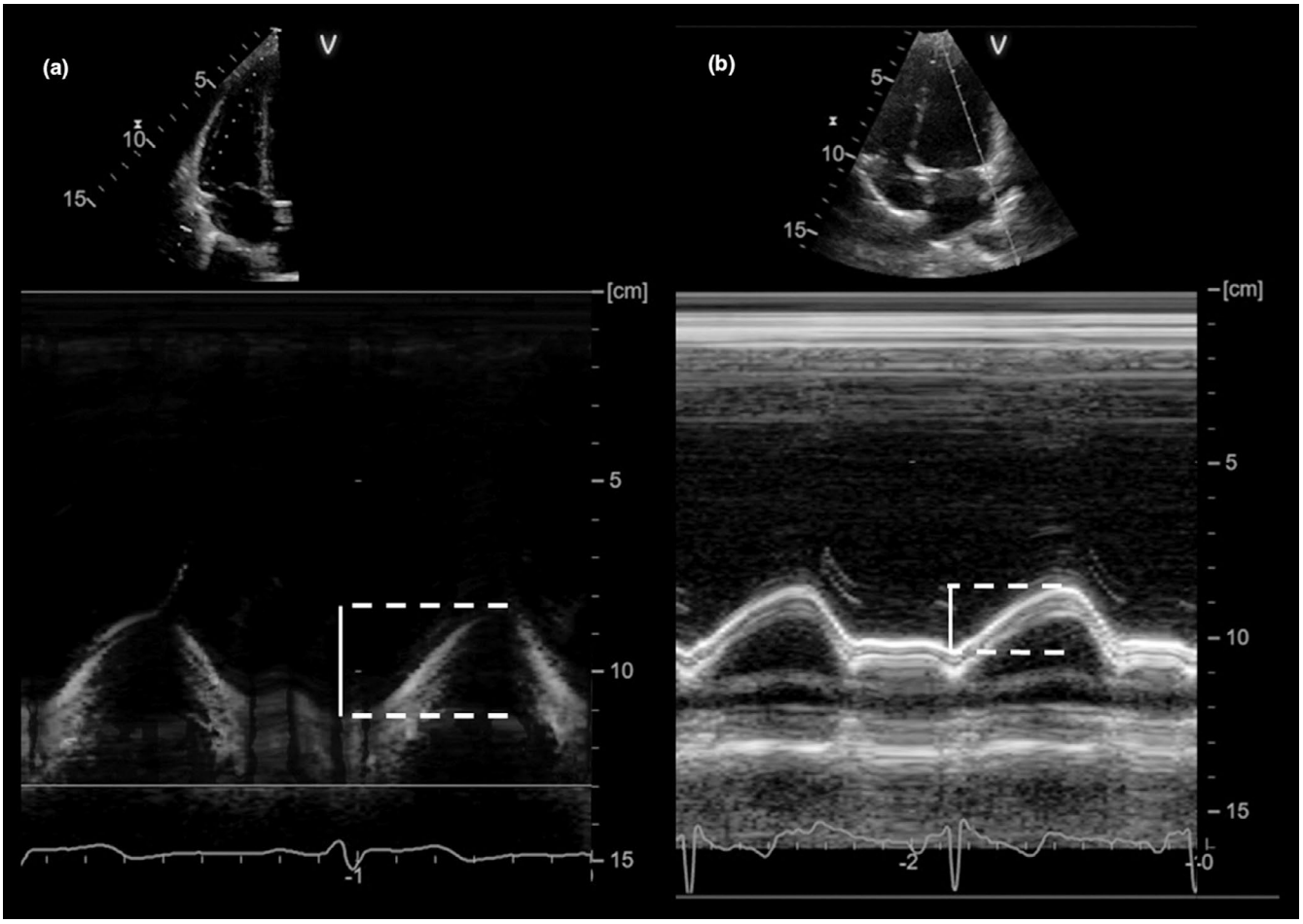

FIGURE 1 Mitral and tricuspid annular plane systolic excursion measurements by M-mode echocardiography. After visualization of the four-chamber view, M-mode is applied at the level of the lateral atrioventricular valve annulus. The distance from the lowest level at R-wave (end-diastole) to the highest displacement (end-systole) is measured for mitral annular plane systolic excursion (a; MAPSE) and tricuspid annular plane systolic excursion (b; TAPSE)

typical flip angle 45°, TE/TR 1.34/51 ms, in plane resolution 2 × 2 × 8 mm, and 25 frames per cardiac cycle.

Both MAPSE and TAPSE were determined semi-automatically, with manual correction if needed, using the freely available software Segment® (Medviso AB, Lund, Sweden) (Heiberg et al., 2010; Seemann et al., 2017). For MAPSE and TAPSE by CMR, reference markers were placed in end-diastole at the left and right lateral walls at the level of the mitral and tricuspid annulus/valvular hinge points in the four-chamber view, respectively (Figure 2), with the automatic time-resolved tracking algorithm applied throughout the cardiac cycle (Figure 3).

For values of MAPSE and TAPSE as based on AVPD analysis, the measurement points were instead of at the annulus placed on the basal top of the compact myocardium in the respective long-axis view (Seemann et al., 2017). Positional landmarks were checked throughout the cardiac cycle, and manual correction was applied if needed after semi-automatic tracking. Lateral values from the four-chamber view were exported for comparison with direct measurements of MAPSE and TAPSE.

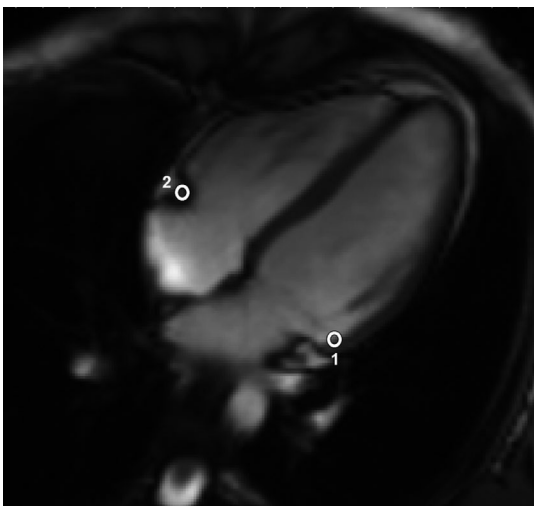

FIGURE 2 Mitral and tricuspid annular plane systolic excursion reference markers at end-diastole for semi-automatic measurement using cardiac magnetic resonance imaging. The reference markers at end-diastole for MAPSE (1) and TAPSE (2) are denoted

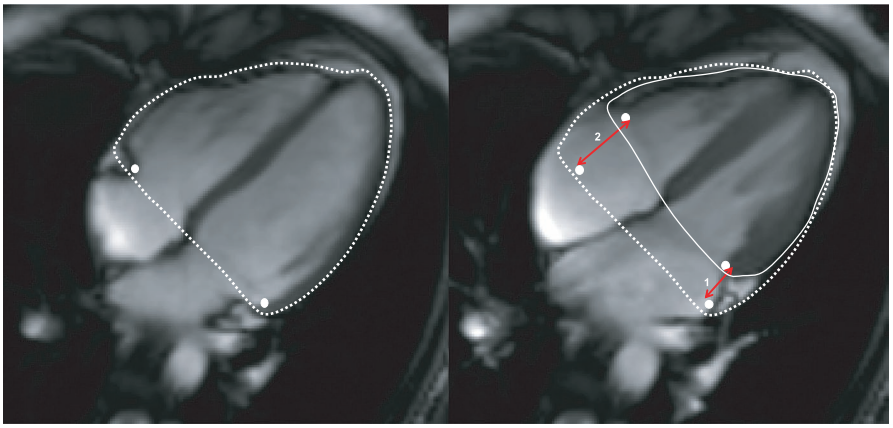

FIGURE 3 Mitral and tricuspid annular plane systolic excursion measurements by the semi-automatic time-resolved algorithm using cardiac magnetic resonance imaging. The outer area of the ventricles is delineated at end-diastole (dotted line) and end-systole (solid line) and reference markers for tracking denoted with closed circles. Two-sided arrows represent peak mitral (1) and tricuspid (2) annular plane systolic excursion tracking. Note how the mitral and tricuspid annulus points differ in position compared with the atrioventricular plane displacement

2.4 | Intra- and inter-observer analysis

A subset of 20 subjects was randomly selected for intra- and inter-observer variability of MAPSE and TAPSE for echocardiography and CMR. One blinded observer (A.S-M.) analysed echocardiography and CMR measurements one week apart for intra-observer variability for both methods. Two other blinded observers provided analyses of echocardiography (B.V-A.) and CMR (K.S-E.) for inter-observer variability.

2.5 | Statistical analyses

The D'Agostino test was performed to test for normal distribution. Variables were expressed as mean ± SD or median [IQR], and statistical differences were tested using Student's t-test. Categorical variables were expressed as n (%).

For comparisons between echocardiography and CMR, Deming regression was used to estimate the fitted up-slope for overcoming the assumptions of a classic linear regression considering measurement errors present in both methods (Cornbleet & Gochman, 1979). For 95% confidence interval (CI) determination, the Jackknife method was used. The coefficient of variation (CoV), as a measure of relative variability, was estimated as a ratio of the standard deviation to the mean. Bias and 95% limits of agreement for MAPSE and TAPSE were calculated and presented in Bland–Altman plots (Bland & Altman, 1986).

Intra- and inter-observer reproducibility was calculated as the concordance correlation coefficient (CCC) (Lin, 1989), with the CCC agreement scale as described by McBride (McBride, 2005). Bias and limits of agreement were calculated and presented using Bland–Altman plots.

To determine the impact of time between echocardiography and CMR on reproducibility, a quantile regression test was performed, considering the time in days between examinations by echocardiography and CMR as the independent variable and the absolute inter-method difference as the dependent variable. Time between examinations was divided in four intervals, based on the largest difference between studies (<26 days, 27–52 days, 53–79 days, >80 days), and a trend analysis with the Jonckheere-Terpstra test performed, considering the absolute time between examinations.

All statistical analyses were performed in Stata 14.2 (Statacorp, College Station, Texas, USA). A two-sided *P*-value < 0.05 was considered to show significant differences.

3 | RESULTS

One hundred and eleven healthy subjects were included in the current study. Median time between echocardiography and CMR was 41 [20–103] days. Quantile regression for MAPSE and TAPSE demonstrated no correlation between measurements and time between examinations ($r = 0.0$; $p = 0.9$, and $r = 0.002$; $p = 0.6$, respectively). Trend analysis confirmed these results, with no trend found after considering time between examinations ($p = 0.4$ and $p = 0.6$ for MAPSE and TAPSE, respectively). Analyses were, therefore, based on all 111 subjects included in the current study. Participants' characteristics are presented in Table 1. There was no difference between heart rate at echocardiography (68 ± 12 bpm) and at CMR (66 ± 11 bpm; $p = 0.1$).

3.1 | Comparison of echocardiography and CMR

Mitral annular plane systolic excursion by manual echocardiography measurements was 17 ± 2 mm vs. 17 ± 2 mm by semi-automatic CMR ($p = 0.16$). Tricuspid annular plane systolic excursion by manual echocardiography measurements was 25 ± 3 mm vs. 25 ± 3 mm by semi-automatic CMR ($p = 0.7$). Deming regression analyses are

shown in Table 2. Coefficient of variation was lower for MAPSE (3.0%) than TAPSE (13.3%). Fitted up-slopes demonstrated a high inter-method correlation for both MAPSE and TAPSE. Figure 4a,b presents Bland-Altman and scatter plots for both measurements.

MAPSE and TAPSE based on semi-automatic AVPD analysis were similar in values, however statistically different, compared with semi-automatic direct measurements by CMR (16 ± 2 mm vs. 17 ± 2 mm; $p = 0.02$, and 24 ± 3 vs. 25 ± 3 mm; $p < 0.001$, respectively). Deming regression analyses are shown in Table 2. Coefficient of variation was low for both MAPSE (2.4%) and TAPSE (2.8%). Fitted up-slopes demonstrated a high inter-method correlation for both MAPSE and TAPSE (Table 2).

Finally, MAPSE by manual echocardiography measurements was 17 ± 2 mm vs. 16 ± 2 mm based on semi-automatic AVPD analysis by CMR ($p = 0.0008$) and TAPSE correspondingly 25 ± 3 mm vs. 24 ± 3 mm ($p = 0.001$). Deming regression analyses are shown in Table 2. Coefficient of variation was low for both MAPSE (3.3%) and TAPSE (1.6%). Fitted up-slopes demonstrated a high inter-method correlation for both MAPSE and TAPSE (Table 2).

TABLE 1 Demographic and anthropometric characteristics of the study population

Characteristics	$n = 111$
Age, years	35 [32–38]
Male sex	60 (54%)
Height, cm	170 ± 9
Weight, kg	70 [58–80]
BMI, kg/m^2	24 [21–26]
Systolic blood pressure, mmHg	104 [95–111]
Diastolic blood pressure, mmHg	73 [68–80]
Current smokers	29 (26%)

Continuous data expressed as mean ± SD or median [IQR], according to distribution. Categorical data expressed as number (percentage). BMI, body mass index.

3.2 | Reproducibility by echocardiography

Both MAPSE and TAPSE by echocardiography demonstrated low intra-observer variability (Table 3 and Figure 5a-b). For MAPSE and TAPSE, the mean intra-observer values for observer 1 and observer 2 were 17 ± 3 mm vs. 16 ± 3 mm and 25 ± 3 mm vs. 25 ± 3 mm, respectively. Inter-observer analysis demonstrated reproducibility for MAPSE (CCC =0.86) and TAPSE (CCC =0.95) (Table 3 and Figure 5c-d).

3.3 | Reproducibility by CMR

Both MAPSE and TAPSE by semi-automatic CMR demonstrated low intra-observer variability (Table 3 and Figure 5e-f). For MAPSE and TAPSE, the mean intra-observer values for observer 1 and observer 2 were 16 ± 2 mm vs. 16 ± 2 mm and 28 ± 4 mm vs. 27 ± 4 mm, respectively. Inter-observer analysis demonstrated reproducibility for MAPSE (CCC =0.85) and TAPSE (CCC =0.95) (Table 3 and Figure 5g,h).

4 | DISCUSSION

This study showed that both MAPSE and TAPSE measurements by echocardiography and semi-automatic CMR analysis have low variability for each method in a population of healthy adult subjects. Further, echocardiography and semi-automatic CMR analysis reported similar values for both MAPSE and TAPSE. The methods are thus interchangeable for follow-up studies. For annular plane systolic excursion as based on values from semi-automatic AVPD by CMR, values are similar to both echocardiography and direct measurement by semi-automatic CMR, although statistically different in the current study. The clinical significance of this statistical difference is, however, likely low.

TABLE 2 Comparison of MAPSE and TAPSE by echocardiography, direct measurement by semi-automatic CMR, and as based on semi-automatic AVPD measurement by CMR

Parameter	CoV (%)	Bias (95% LoA) by Bland–Altman	Intercept (95% CI) by Deming regression	Fitted-slope (95% CI) by Deming regression
Manual echocardiography vs. direct measurement by semi-automatic CMR				
MAPSE	3.0	0.415 (−2.052 to 2.883)	−3.35 (−5.918 to − 0.787)	1.22 (1.066 to 1.379)
TAPSE	13.3	−0.177 (−4.782 to 4.429)	−3.31 (−7.608 to 0.979)	1.12 (0.954 to 1.292)
Manual echocardiography vs. based on semi-automatic AVPD measurement by CMR				
MAPSE	2.4	1.028 (−3.748 to 5.805)	−4.80 (−13.360 to 3.763)	1.36 (0.825 to 1.890)
TAPSE	2.8	1.458 (−6.425 to 9.341)	−0.10 (−17.995 to 17.795)	1.07 (0.314 to 1.816)
Direct measurement by semi-automatic CMR vs. based on semi-automatic AVPD measurement by CMR				
MAPSE	3.3	0.613 (−3.398 to 4.624)	1.91 (−2.660 to 6.480)	0.92 (0.638 to 1.203)
TAPSE	1.6	1.635 (−3.505 to 6.774)	4.04 (−6.958 to 8.770)	0.90 (0.702 to 1.096)

AVPD, atrioventricular plane displacement; CI, confidence interval; CMR, cardiac magnetic resonance; CoV, coefficient of variation; LoA, limits of agreement; MAPSE, mitral annular plane systolic excursion; TAPSE, tricuspid annular plane systolic excursion.

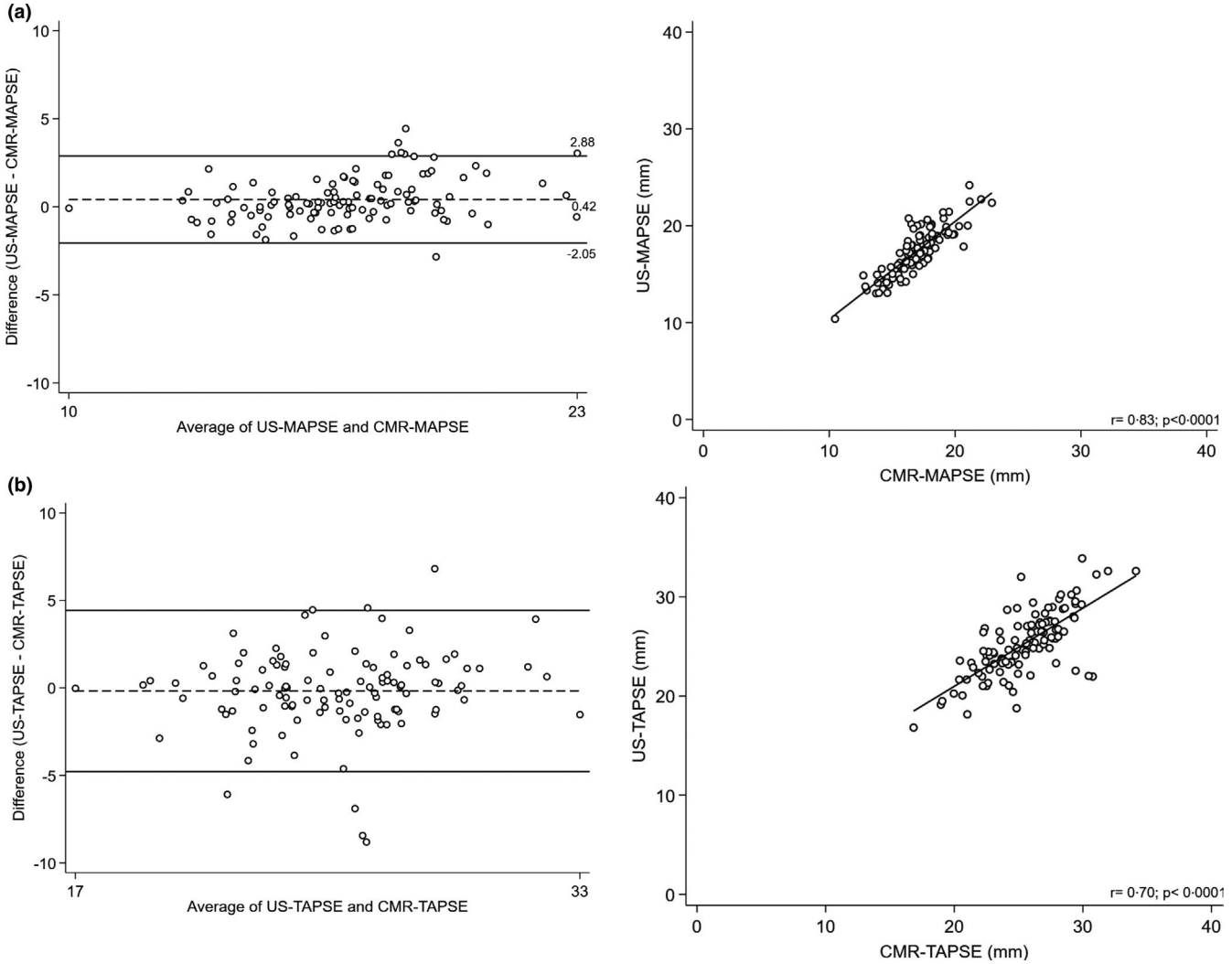

FIGURE 4 Bland–Altman and scatter plots for comparison of mitral and tricuspid annular plane systolic excursion by echocardiography and cardiac magnetic resonance imaging. Bland–Altman plots with 95% limits of agreement (left) and scatter plots with regression lines (right) are presented for mitral (a) and tricuspid (b) annular plane systolic excursion. Echocardiography and magnetic resonance imaging show similar values for assessment of mitral and tricuspid annular plane systolic excursion

The current study showed similar values for MAPSE and TAPSE by time-resolved semi-automatic tracking by both direct measurements and based on AVPD analysis by CMR as compared with echocardiography, despite that data from the different modalities were not acquired the same day. Ochs *et al* compared manual measurements for MAPSE and TAPSE by echocardiography and CMR acquired the same day in 30 patients and showed CoV (bias; 95% LoA) to be 10.3% (−0.8; −5.7 to 4.0) for MAPSE, and 11.0% (1.3; −6.4 to 9.1) for TAPSE (Ochs et al., 2017). These previous results were thus, despite assessed the same day, of larger variability than the current results. Interestingly, the coefficient of variation between methods was larger between direct measurements by CMR and echocardiography, than between measurements based on AVPD analysis by CMR and echocardiography. However, as indicated by both bias and intercept by Deming regression, the statistically significant differences between methods and modalities are likely not of clinical significance.

Regarding the semi-automatic CMR method used in the current study, it is important to acknowledge that in the original protocol by Seemann et al., (2017), a cine acquisition with 30 images per cardiac cycle was used, whereas, the current protocol used 25 images per cardiac cycle. This is related to scanner settings for clinical routine and is still used in many centres. Nevertheless, this relatively lower setting for temporal resolution could be associated with that the real maximum MAPSE and TAPSE are missed. As echocardiography has a substantially higher temporal resolution this might have affected the comparison between methods. Seemann et al., (2017) also showed correlation between CMR and echocardiography for lateral e´ and E/e´ ($r = 0.76$; $p < 0.0001$ and $r = 0.85$; $p < 0.0001$) for diastolic function in 59 patients. No comparison was, however, performed for longitudinal systolic function.

There are technical differences between 2D echocardiography and CMR. Despite that echocardiography has a higher temporal resolution than CMR, it may have acoustic window limitations, mainly in extremely thin or obese patients, which could affect acquisition

TABLE 3 Intra- and inter-observer reproducibility of MAPSE and TAPSE by echocardiography and cardiac magnetic resonance ($n = 20$)

	CCC (95% CI)	CCC p-value	Standard Error	Bias (95% LoA)
Echocardiography				
Intra-observer analysis				
MAPSE	0.963 (0.930 to 0.996)	<0.0001	0.017	0.194 (−1.124 to 1.513)
TAPSE	0.960 (0.926 to 0.994)	<0.0001	0.018	0.155 (−1.449 to 1.758)
Inter-observer analysis				
MAPSE	0.864 (0.748 to 0.980)	<0.0001	0.059	0.381 (−2.114 to 2.876)
TAPSE	0.951 (0.907 to 0.995)	<0.0001	0.022	0.127 (−1.788 to 2.041)
Cardiac magnetic resonance				
Intra-observer analysis				
MAPSE	0.873 (0.763 to 0.982)	<0.0001	0.056	−0.137 (−2.055 to 1.781)
TAPSE	0.969 (0.942 to 0.996)	<0.0001	0.014	0.245 (−1.571 to 2.061)
Inter-observer analysis				
MAPSE	0.854 (0.731 to 0.977)	<0.0001	0.063	0.184 (−2.011 to 2.378)
TAPSE	0.958 (0.920 to 0.995)	<0.0001	0.019	−0.060 (−2.265 to 2.144)

CCC, concordance correlation coefficient; CI, confidence interval; LoA, limits of agreement.

of an adequate four-chamber view focused on the right ventricle for TAPSE measurements. In contrast, four-chamber acquisitions with CMR can always be rotated to the largest right ventricle with the left ventricle in the rotational centreline. According to chamber quantification, right ventricular assessment should be performed in a view focused on the right ventricle with special care to avoid the standard four-chamber view with an potentially under-rotated right ventricle (Medvedofsky et al., 2015). Foreshortening and off-angle slice positions may affect both echocardiography and CMR, particularly on the right side, and there is thus a risk that TAPSE is measured in a different location by echocardiography and CMR in the current study. This may in part explain the higher correlation between methods for MAPSE than TAPSE in the current study. Outliers in Figure 4, for example with TAPSE approximately 22 mm by echocardiography and 30 mm by CMR may also be explained by this difference between methods.

Semi-automatic CMR algorithms for assessment of both systolic and diastolic function are increasingly available and may both decrease user variability and analysis time. Although echocardiography is widely available and easy to utilize for assessing MAPSE and TAPSE, the current study provides information that both CMR and echocardiography can be used longitudinally in the same patient, which may simplify future studies and clinical application. Further, although manual correction for MAPSE and TAPSE is needed in the applied AVPD algorithm, with manual correction or by direct measurement of MAPSE and TAPSE by CMR, follow-up examinations are likely independent of modality.

4.1 | Limitations

As echocardiography and CMR were not performed the same day, physiological variation may have had an impact on comparisons. To minimize this, subjects were advised to not exercise before examinations, and there is no obvious bias in the results indicating significant change in cardiac function between assessments. Time between echocardiography and CMR could be a potential bias in itself. Quantile regression and trend analysis, however, showed no impact of time between examinations on measurements. The CMR protocol used a lower temporal resolution for cine acquisition than used in the original publication, possibly affecting the correct estimation of maximum excursion of the mitral and tricuspid annuli by CMR. Although increased temporal resolution is advocated, there is no significant systematic bias in the current results indicating that this is crucial for the comparison between methods. Only the apical four-chamber view was used, whereas MAPSE can also be performed using the apical two-chamber view. In the larger inclusion study, however, only the 4-chamber view was assessed.

5 | CONCLUSION

This study showed that both mitral and tricuspid atrioventricular plane systolic excursion (MAPSE and TAPSE) measurements by echocardiography and CMR have low variability for each method in a population of healthy subjects. Echocardiography and CMR reported similar values for both MAPSE and TAPSE and measurements by the two methods are thus interchangeable. For annular plane systolic excursion as based on values from semi-automatic AVPD by CMR, values are similar to both echocardiography and direct measurement by semi-automatic CMR, although statistically different in the current study. The clinical significance of this statistical difference is, however, likely low. It may thus be assumed that lateral values based on semi-automatic AVPD analysis by CMR could be used as a representation of annular displacement.

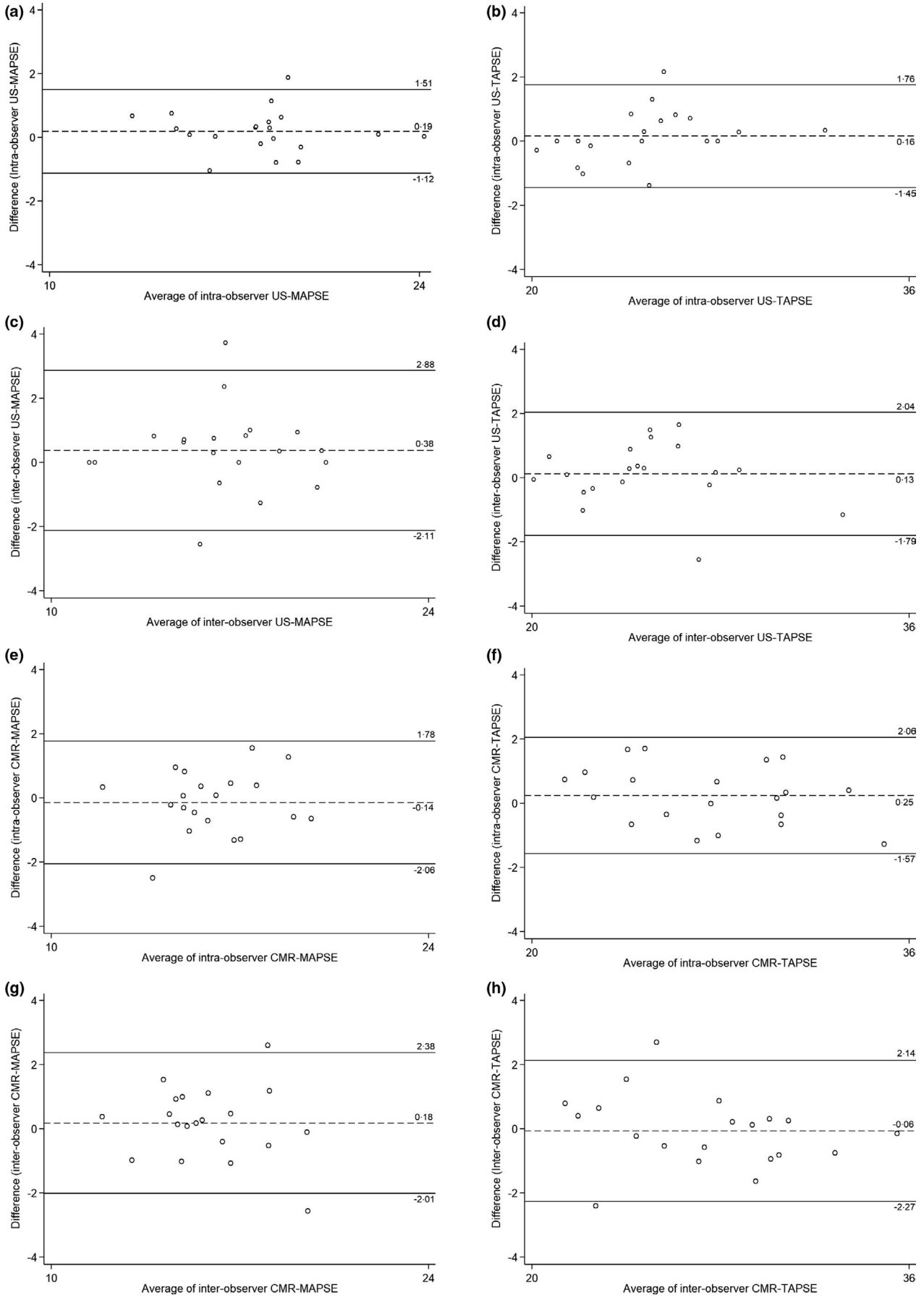
(a)
Difference (intra-observer US-MAPSE)
1·51
0·19
-1·12
Average of intra-observer US-MAPSE
(b)
Difference (intra-observer US-TAPSE)
1·76
0·16
-1·45
Average of intra-observer US-TAPSE
(c)
Difference (inter-observer US-MAPSE)
2·88
0·38
-2·11
Average of inter-observer US-MAPSE
(d)
Difference (inter-observer US-TAPSE)
2·04
0·13
-1·79
Average of inter-observer US-TAPSE
(e)
Difference (intra-observer CMR-MAPSE)
1·78
-0·14
-2·06
Average of intra-observer CMR-MAPSE
(f)
Difference (intra-observer CMR-TAPSE)
2·06
0·25
-1·57
Average of intra-observer CMR-TAPSE
(g)
Difference (inter-observer CMR-MAPSE)
2·38
0·18
-2·01
Average of inter-observer CMR-MAPSE
(h)
Difference (inter-observer CMR-TAPSE)
2·14
-0·06
-2·27
Average of inter-observer CMR-TAPSE

FIGURE 5 Bland–Altman plots for intra- and inter-observer reproducibility for mitral and tricuspid annular plane systolic excursion by echocardiography and cardiac magnetic resonance imaging. Intra-observer (a, b) and inter-observer (c, d) reproducibility for mitral (a, c) and tricuspid (b, d) annular plane systolic excursion by M-mode echocardiography. Intra-observer (e, f) and inter-observer (g, h) reproducibility for mitral (e, g) and tricuspid (f, h) annular plane systolic excursion by magnetic resonance imaging. Echocardiography and magnetic resonance imaging both show high intra- and inter-observer reproducibility for mitral and tricuspid annular plane systolic excursion

6 | DECLARATIONS

6.1 | Consent for publication

All participants provided written consent for publication of any data obtained during the study.

ACKNOWLEDGMENTS

This project has been co-funded with support of the Erasmus + Programme of the European Union (Framework Agreement number: 2013-0040). This publication reflects the views only of the authors, and the Commission cannot be held responsible for any use that may be made of the information contained therein.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

ASM, FC and EH contributed substantially to the study design. ASM drafted the manuscript. ASM, KSE, BVA and EH analysed data. All authors interpreted data and revised the manuscript critically for important intellectual content, have provided final approval of the version to be published and have agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

DATA AVAILABILITY STATEMENT

The data sets generated and analysed during the current study are not publicly available due to the Spanish law of data protection in research but are available from the corresponding author on reasonable request.

ORCID

Alvaro Sepúlveda-Martínez https://orcid.org/0000-0002-8364-2732
Ellen Ostenfeld https://orcid.org/0000-0002-2655-2423
Erik Hedström https://orcid.org/0000-0003-0041-9357

REFERENCES

Bland, J.M. & Altman, D.G. (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, *1*, 307–310.

Carlsson, M., Ugander, M., Heiberg, E. & Arheden, H. (2007a) The quantitative relationship between longitudinal and radial function in left, right, and total heart pumping in humans. *American Journal of Physiology. Heart and Circulatory Physiology*, *293*, H636–644.

Carlsson, M., Ugander, M., Mosén, H., Buhre, T. & Arheden, H. (2007b) Atrioventricular plane displacement is the major contributor to left ventricular pumping in healthy adults, athletes, and patients with dilated cardiomyopathy. *American Journal of Physiology. Heart and Circulatory Physiology*, *292*, H1452–1459.

Cornbleet, P.J. & Gochman, N. (1979) Incorrect least-squares regression coefficients in method-comparison analysis. *Clinical Chemistry*, *25*, 432–438.

Dutta, T. & Aronow, W.S. (2017) Echocardiographic evaluation of the right ventricle: Clinical implications. *Clinical cardiology*, *40*, 542–548.

Feigenbaum, H., Zaky, A. & Nasser, W.K. (1967) Use of ultrasound to measure left ventricular stroke volume. *Circulation*, *35*, 1092–1099.

Heiberg, E., Sjögren, J., Ugander, M., Carlsson, M., Engblom, H. & Arheden, H. (2010) Design and validation of Segment–freely available software for cardiovascular image analysis. *BMC Medical Imaging*, *10*, 1.

Kaul, S., Tei, C., Hopkins, J.M. & Shah, P.M. (1984) Assessment of right ventricular function using two-dimensional echocardiography. *American Heart Journal*, *107*, 526–531.

Lin, L.I. (1989) A concordance correlation coefficient to evaluate reproducibility. *Biometrics*, *45*, 255–268.

McBride, G.B. (2005) A proposal for strength-of-agreement criteria for Lin's Concordance Correlation Coefficient. *Biometrics*, *45*, 307–310.

Medvedofsky, D., Addetia, K., Patel, A.R., Sedlmeier, A., Baumann, R., Mor-Avi, V. et al. (2015) Novel approach to three-dimensional echocardiographic quantification OF right ventricular volumes and function from focused views. *Journal of the American Society of Echocardiography*, *28*, 1222–1231.

Ochs, M.M., Fritz, T., André, F., Riffel, J., Mereles, D., Müller-Hennessen, M. et al. (2017) A comprehensive analysis of cardiac valve plane displacement in healthy adults: age-stratified normal values by cardiac magnetic resonance. *International Journal of Cardiovascular Imaging*, *33*, 721–729.

Romano, S., Judd, R.M., Kim, R.J., Kim, H.W., Heitner, J.F., Shah, D.J. et al. (2019) Prognostic implications of mitral annular plane systolic excursion in patients with hypertension and a clinical indication for cardiac magnetic resonance imaging: A multicenter study. *JACC: Cardiovascular Imaging*, *12*, 1769–1779.

Seemann, F., Pahlm, U., Steding-Ehrenborg, K., Ostenfeld, E., Erlinge, D., Dubois-Rande, J.-L. et al. (2017) Time-resolved tracking of the atrioventricular plane displacement in Cardiovascular Magnetic Resonance (CMR) images. *BMC Medical Imaging*, *17*, 19.

Steding-Ehrenborg, K., Boushel, R.C., Calbet, J.A., Åkeson, P. & Mortensen, S.P. (2015) Left ventricular atrioventricular plane displacement is preserved with lifelong endurance training and is the main determinant of maximal cardiac output. *Journal of Physiology*, *593*, 5157–5166.