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CARDIAC

CT compared to MRI for functional evaluation of the right ventricle: a systematic review and meta-analysis

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Abstract

Objective Right ventricular function (RVF) is a strong predictor of adverse cardiac events; however, the reference standard for RVF assessment, MRI, is limited in some patients for whom accurate evaluation of RVF is essential, like those with COPD or non-MR compatible metal implants. We conducted this meta-analysis to evaluate whether CT was as accurate as MRI for the assessment of RVF.

Method We conducted a meta-analysis of studies retrieved from PubMed, Embase, and Cochrane Central searches to evaluate the differences and correlations between the following RVF parameters as measured by CT and MRI: end diastole volume (EDV), end systole volume (ESV), right ventricular ejection fraction (RVEF), and stroke volume (SV).

Results Sixteen studies that used disk summation (637 subjects) and three studies that used three-dimensional reconstruction were included. For the 16 studies, the pooled standard mean differences (95% confidence interval) were 1.04 (− 2.59, 4.67) for EDV, 1.22 (1.50, 3.95) for ESV, − 0.65 (− 2.60, 1.29) for RVEF, and − 0.37 (− 3.64, 2.90) for SV. The overall correlation coefficient (r) values were 0.98 for EDV, 0.95 for ESV, 0.98 for RVEF, and 0.97 for SV. The mean difference between the two methods was not statistically significant (overall effect Z test, $p > 0.1$).

Conclusion CT can assess RVF with accuracy comparable to that of MRI. Thus, CT is a valid alternative to MRI.

Key Points

• *CT could help clinicians to assess RVF as accurately as MRI can, with satisfactory repeatability.*

Keywords Right ventricular function · Computed tomography · Magnetic resonance imaging · Meta-analysis

Abbreviations

CI	Confidence interval
CT	Computed tomography
EDV	End diastole volume
ESV	End systole volume
LOA	Limit of agreement

Hang Fu and Xuedong Wang contributed equally to this work and should be considered the co-first authors.

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MD	Mean difference
MR	Magnetic resonance
MRI	Magnetic resonance imaging
QUADAS	The Quality Assessment of Diagnostic Studies
RV	Right ventricular
RVEF	Right ventricular ejection fraction
RVF	Right ventricular function
SD	Standard deviation
SV	Stroke volume
TR	Temporary resolution

Introduction

Right ventricular (RV) function (RVF) is closely related to the development, treatment, and prognosis of cardiovascular diseases, including myocardial infarction, valvular heart disease, cardiomyopathy, and even congenital heart disease, especially when accompanied by pulmonary artery hypertension [1]. Several studies have demonstrated additional predictive values of RVF indexes on long-term survival of patients with myocardial infarction, dilated cardiomyopathy, and chronic heart failure [2–5]. Indexes of RVF also aid in the selection of patients with asymptomatic mitral regurgitation for valvular surgery [6]. Subclinical changes in RVF have been found in some systemic diseases, such as diabetes and systemic sclerosis [7, 8]. Therefore, timely and accurate assessment of RVF is of great clinical significance.

Echocardiography is a routine modality for the evaluation of cardiac function but is of limited accuracy for assessing RVF due to the complex geometry of the RV, the diversity of individual acoustic windows, low spatial resolution (especially at the endocardium), and high intra-observer variability [9]. Alternatively, MRI is an ideal imaging modality with satisfactory spatial and soft tissue resolution. With continued technical advances, MRI is gradually becoming the reference standard for right and left ventricular functional assessment, with excellent repeatability and reproducibility [10, 11]. However, MRI is contraindicated in patients with non-MR compatible metal implants, and MR-conditional devices would induce artifacts despite the absence of adverse events, such as device movement and effects related to the heating effect and electromagnetic effect [12]. MRI is also limited in patients with claustrophobia, severe congestive heart failure, and dyspnea who cannot withstand prolonged examination in the supine position and repeated breath-holding, for whom RVF evaluation could be of great importance. Finding an alternative imaging modality to assess RVF is helpful.

CT coronary angiography provides excellent spatial resolution and good temporal resolution for comprehensive assessment of cardiac function. CT allows rapid data collection without compromising image quality [13]. A previous meta-analysis demonstrated the feasibility of CT for RVF assessment, but focused only on the RV ejection fraction (RVEF) [14]. CT performance for measuring other RVF indexes like end diastole volume (EDV), end systole volume (ESV), and stroke volume (SV) is unclear. We conducted this systematic review and meta-analysis to comprehensively assess the reliability of CT for RVF evaluation compared to MRI.

Methods

This study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines (see Table 1 in Online supplementary material) [15].

Search strategy

Systematic searches were conducted in PubMed, Embase, and Cochrane Central for articles comparing RVF as measured by CT and MRI between January 1990 and January 2018 without restriction. Two authors completed the task independently and disagreements were resolved by consulting a third author.

Relevant combinations of the following keywords, either in MESH or "free text," were used to accomplish the search: magnetic resonance imaging, MRI; cardiac magnetic resonance, CMR; computed tomography, CT; multi-detector computed tomography, MDCT; multi-slice computed tomography, MSCT; dual-source CT, right ventricular function, right ventricular volume, right ventricular ejection fraction, and RVEF.

Study selection

Studies were selected if they met the following criteria: (1) basic scan parameters of CT and MRI were indicated, including slice thickness, slice gap, field strength of MR scanner, and slices of CT scanner; (2) the demographic information of recruited subjects was available; (3) the interval between CT and MRI was less than 1 month; and (4) Bland–Altman analysis was used to evaluate consistency of the two modalities [16]. Animal experiments and papers in language other than English were excluded. Abstracts of meetings were not included because data for the Bland–Altman analysis could not be extracted. Both prospective and retrospective observational cohort studies were included in the meta-analysis if they met the inclusion criteria. There was no restriction on the study population; studies involving adults or children and patients or healthy people were included if they met the inclusion criteria.

Quality assessment

The risk of bias of each included study was evaluated by items (see Table 2 in Online supplementary material) of The Quality Assessment of Diagnostic Studies (QUADAS) by Review Manager 5.3, which is used to assess the quality of diagnostic studies [17].

Data extraction

The following data were extracted from each study: first author, publication year, journal, number of recruited subjects, demographic and disease information of recruited subjects, medications taken, interval between CT and MRI measurements, and basic scan parameters of CT and MRI. The mean difference (MD) and limits of agreement (LOA) of RVEF, EDV, ESV, and SV between the two modalities were extracted from the Bland–Altman analysis to summarize the results of included studies. Moreover, we also calculated Pearson's correlation coefficient (r) values between CT and MRI for each RVF parameter as well as the 95% confidence interval (CI) using Fisher's r-to-z transformation according to the following formulae [18]:

$$z = 0.5 \times \ln\left(\frac{1+|r|}{1-|r|}\right) \quad zl = z - \frac{1.96}{\sqrt{N-3}}$$

$$zu = z + \frac{1.96}{\sqrt{N-3}}$$

$$\text{CIs of } r: \left(\frac{e^{2zl}-1}{e^{2zu}+1} to \frac{e^{2zu}-1}{e^{2zu}+1}\right)$$

Statistical analysis

Continuous variables were presented as the mean ± standard deviation (SD) and dichotomous variable was presented as percentages. The MD, LOA, and r values from individual studies were weighted according to the number of subjects in the sample. The pooled effects of EDV, ESV, RVEF, and SV were calculated according to a fixed model. The Cochrane Q test was used to determine heterogeneity and was expressed as I^2. A $p < 0.05$ for the Q test or $I^2 > 50\%$ was regarded as indicative of moderate to severe heterogeneity among the included studies. In such cases, a random model was applied or further subgroup analysis was considered. Publication bias was assessed by constructing a funnel plot for each RVF parameter. We performed subgroup analysis according to the algorithm used for cardiac function (disk summation or 3D reconstruction) and CT slice/detector number. All statistical analyses were conducted using Stata version 13.

Results

Study selection

In total, 512 citations were identified after the systematic search, and 463 were potentially eligible after excluding duplicates. A total of 340 papers were excluded after screening the title and abstract for irrelevance, non-English language, or CT and MRI were performed on animal models. Twenty-three articles were selected for full-text review. After further evaluation with reference to the inclusion criteria, 4 additional publications were excluded. Finally, 19 studies were included in this meta-analysis. The flow chart of the literature search and study selection is presented in Fig. 1 [19–37].

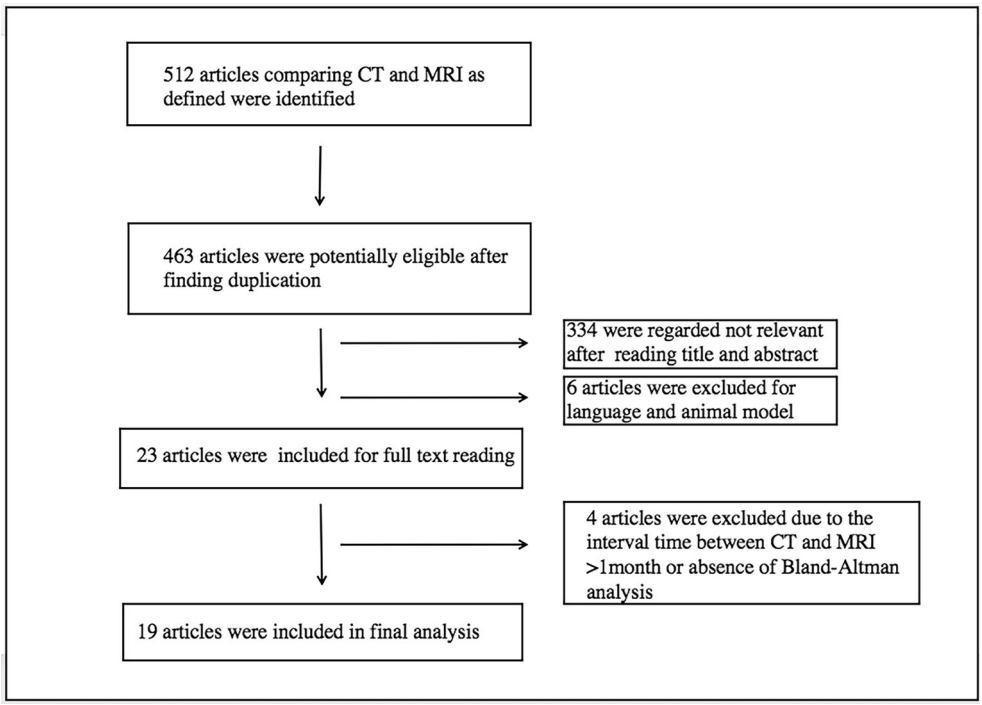

Fig. 1 Flow chart of study selection

Study quality and characteristics

The results of the quality assessment and basic characteristics of the selected studies are illustrated in Fig. 2 and Table 1. The 19 selected studies included 749 patients (469 men; mean age, 53.9 years) with a wide spectrum of cardiovascular diseases (coronary artery disease, dilated cardiomyopathy, congenital heart disease, and valvular disease among others). All studies excluded patients with contradictions for MRI or iodine contrast agent. All included subjects in each study completed RVF analysis except for those with poor image quality in the studies of Raman et al and Kock et al [22, 32].

A 1.5-Tesla system was applied in all studies except for that of Yamasaki et al [36], which utilized a 3-Tesla system. Sixteen studies provided the number of slices or detectors (8, 16, 64, 128, or 256) of the CT scanner while 3 studies did not [20, 27, 35]. Acquisition parameters, including slice thickness, slice gap, and heart phase, that have the highest effect on RVEF were shown in Table 1. To lower the subjects' heart rate during scanning, 5 studies administered β-blockers before CT examination [20, 21, 28, 31, 32]. The breath-holding state during the CT and MRI scanning procedures differed among studies, and some only indicated a breath-holding state during MRI examination. Three studies applied 3D reconstruction instead of disk summation for CT analysis [25, 33, 36]. All studies applied different contrast agent injection protocols, and the detailed information was presented in Table 3 in Online supplementary material.

Quantitative results

The included studies reported a wide range of RVF index values, with RVEF ranging from 24 to 58.7%, EDV 80–172.7 ml, ESV 15.5–131 ml, and SV 37–99.2 ml. Five papers reported EDV, ESV, and RVEF but not SV [20, 26, 32, 33, 39].

One study reported a comparison between two subgroups: normal subjects versus patients with mitral valve regurgitation [37]. This amounted to two specific cohorts.

The pooled results for all 19 studies were summarized below. The overall MD (and LOA) were 3.30 (0.92, 5.67) for EDV, 4.87 (2.60, 7.14) for ESV, − 1.65 (− 3.02, − 0.28) for RVEF, and 1.45 (− 1.06, 3.95) for SV, with mild heterogeneity (40.0% for EDV and 24.7% for ESV).

Subgroup analysis was conducted according to the CT scanning algorithm used. Among the included studies, 16 applied disk summation and 3 applied 3D reconstruction. Heterogeneity was negligible for all RVF indexes among the 16 studies that employed disk summation. The pooled results (95% CI) were as follows: 1.04 (− 2.59, 4.67) for EDV, 1.22 (1.50, 3.95) for ESV, − 0.65 (− 2.60, 1.29) for RVEF, and − 0.37 (− 3.64, 2.90) for SV. The pooled results of the 3 studies that applied 3D reconstruction were 16.05 (10.59, 21.51) for EDV, 13.02 (8.94, 17.10) for ESV, − 2.63 (− 4.56, − 0.70) for RVEF, and 4.01 (0.12, 7.90) for SV. The homogeneity of the pooled results was negligible except for EDV (5.4%).

Among the 16 studies that used disk summation, we conducted subgroup analysis to determine the effect of CT scanner slice/detector number < 64 (subgroup A) or ≥ 64 (subgroup B). The overall results and heterogeneity are presented in Table 2. The overall MD (and LOA) of subgroup B were 0.60 (− 3.27, 4.47) for EDV, 0.67 (− 2.49, 3.83) for ESV, − 0.17 (− 2.52, 2.18) for RVEF, and − 0.47 (− 3.98, 3.05) for SV. For subgroup A, the pooled results were 4.30 (− 6.19, 14.78) for EDV, 3.28 (− 4.53, 11.09) for ESV, − 1.60 (− 6.39, 3.18) for RVEF, and 0.02 (− 9.97, 10.00) for SV.

The overall heterogeneity of all 19 studies was greatly affected by the 3 studies that applied a 3D reconstruction algorithm. When the 3 studies were excluded, the heterogeneity decreased, and the pooled results of all RVF indexes improved (Fig. 3). In addition, a funnel plot (Fig. 4) suggested that one of the 3 studies may have publication bias. Although there was a marked variation in the correlation coefficient for each RVF index across studies, the overall results indicated a strong relationship between CT and MRI measures of EDV (0.98 [0.98, 0.98]), ESV (0.96 [0.96, 0.97]), RVEF (0.98 [0.97, 0.99]), and SV (0.97 [0.96, 0.97]) (forest plots shown in Fig. 5).

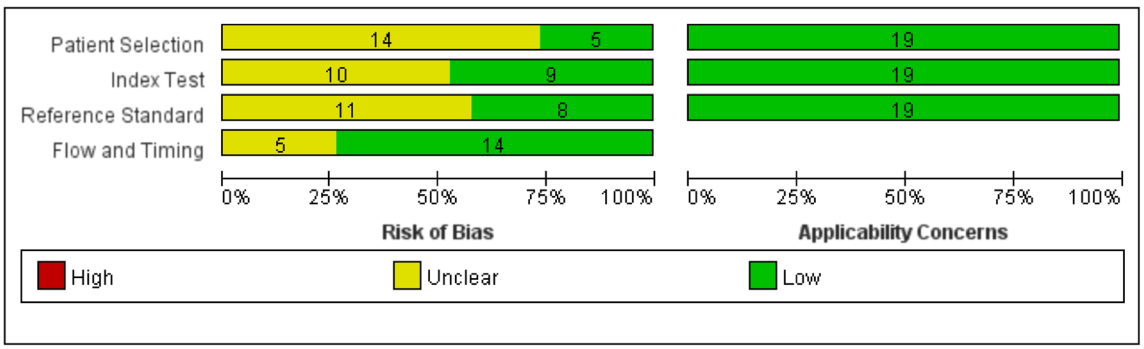

Fig. 2 Quality assessment of 19 studies by QUADAS; Red Bar = High Risk, Yellow Bar = Unclear Risk, Green Bar = Low Risk

Table 1 Characteristics of included studies

Study, first author	Publication year	Journal	Pro or retro	*N*	Age (years)	Sex (male)	Study subject	Interval	β-blocker	CT	MRI
Zhang XC	2012	Chinese Medical Journal	Pro	43	51 ± 8	20	RMS	≤ 1 day	None	Philips 64-slice MDCT; Software Philips Medical System; slice thickness 9 mm; slice gap 0 mm; 10 phases	Siemens 1.5 T; Software Siemens Argus; TrueFISP cine sequence; slice thickness 9 mm; slice gap 0 mm; unk
Yamasaki Y	2014	Eur Radiol	Pro	33	28.9 ± 13.1	19	Repaired TOF	≤ 7 days	None	Philips 256-slice MSCT; Software Extended Brilliance Workspace, Philips Healthcare; slice thickness 2 mm; slice gap 1 mm; 10 phases	Philips 3.0 T; Software Extend Brilliance Workspace, Philips Healthcare; Cine balanced turbo field-echo sequence; slice thickness 8 mm; slice gap unk; 20 phases
Guo YK	2010	Int J Cardiol	Pro	47	49 ± 11	28	Normal 32 CAD 14 HCM 1	≤ 1 day	None	Philips 64-slice MDCT; Software Philips Cardiac Review; slice thickness 9 mm; slice gap 0 mm; 10 phases	Siemens 1.5 T; Software Argus Siemens; TrueFISP cine sequences; slice thickness 9 mm; slice gap 0 mm; unk
Guo YK1	2013	Int J Cardiol	Pro	84	40.5	40	MR 54 control 30	≤ 1 day	None	Philips 64-slice MDCT; Software Philips Cardiac Review; slice thickness 9 mm; slice gap 0 mm; 10 phases	Siemens 1.5 T Sonata; Software Argus Siemens; TrueFISP cine sequences; slice thickness 9 mm; slice gap 0 mm; unk
Gao Y	2012	Eur J Radiol	Pro	58	COPD52 ± 10CP 66 ± 7	39	COPD 46 CP 12	≤ 1 day	HR > 70 bpm	GE 64-slice MDCT; Software GE Healthcare; slice thickness 5 mm; slice gap 0 mm; unk	Siemens Sonata 1.5 T; Software Siemens Argus; SSFP sequences; slice thickness 8 mm; slice gap 0 mm; unk;
Huang XY	2012	Int J Cardiov-asc Imaging	Pro	50	55 ± 9.6	23	Suspected PAD	≤ 1 day	None	Toshiba 320-slice volume cardiac CT; Software VITAL-fx workstation; slice thickness 0.5 mm; slice gap unk; 20 phases	Siemens 1.5 T Sonata; Software Argus Siemens; TrueFISP cine sequences; slice thickness 5 mm; slice gap 0 mm; unk
Raman S V	2006	Am Heart J	Pro	18	60 ± 12	15	Known or suspected CAD	≤ 1 day	HR > 65 bpm	GE 16 slice CT; Software GE Healthcare; slice thickness 8 mm; slice gap 0 mm; 10 phases	GE 1.5 T; Software GE Healthcare; SSFP sequences; slice thickness 8 mm; slice gap 0 mm; 20 phases
Takx R A P	2012	Eur J Radiol	Pro	20	60.6 ± 6.5	16	Known or suspected CAD	≤ 1 day	None	Siemens DSCT; Software Siemens Argus; slice thickness 1.5 mm; slice gap 0 mm; 10 phases	Siemens 1.5 T; Software Siemens Argus; SSFP sequences; slice thickness 8 mm; slice gap 0; 25 phases
Müller M	2009	Eur Radiol	Pro	50	62 ± 9	34	Suspected CAD	≤ 1 day	None	Toshiba 16-slice spiral CT; Software Version CSCF-001A, Toshiba; slice thickness 8 mm; slice gap unk; 10 phases	Siemens 1.5 T Sonata; Software Siemens Argus; TrueFISP sequences; slice thickness 8 mm; slice gap 0 mm; unk
Wang L	2013	J Nuci Cardiol	Pro	23	31.7 ± 11.7	4	PH	≤ 7 days	unk	Siemens 64-slice MDCT; Software Syngo.via cardiovascular engine; slice thickness 2.5 mm; slice gap 0 mm; 20 phases	Siemens 1.5 T; Software Siemens Argus; TrueFISP sequence; slice thickness 8 mm; slice gap 0 mm; 25 phases
Sugeng L	2010	J A C C	Pro	28	53 ± 18	19	CHF PH CHD CAD	≤ 1 day	None	Toshiba 16-slice CT; Software TomTec, Unterschleissheim, Germany; slice thickness 5 mm; slice gap unk; 10 phases	Siemens 1.5 T; Software TomTec, Unterschleissheim, Germany; SSFP sequence; slice thickness 10 mm; slice gap 0 mm; unk
Koch K	2005	Eur Radiol	Pro	18	69	14	CAD 1 coronary bypass 17	≤ 1 day	None	Philips 16-detector-row CT; Software Cardiac Review, Philips Medical Systems; slice thickness 8 mm; slice gap 8 mm; 10 phases	Siemens 1.5 T Sonata; Software Argus Siemens; TrueFISP cine sequences; slice thickness 8 mm; slice gap 8 mm; unk

Table 1 (continued)

Study, first author	Publication year	Journal	Pro or retro	*N*	Age (years)	Sex (male)	Study subject	Interval	β-blocker	CT	MRI
Schroeder J	2009	Clin Res Cardio	Pro	24	64.8 ± 9.5	14	DCM HHD CAD	≤7 days	None	Siemens 16-slice CT; Software Linux; slice thickness 8 mm; slice gap 8 mm; 20 phases	Philips 1.5 T; Software Linux; balance fast-field echo sequence; slice thickness unk; slice gap unk; 15 phases
Jensen C J	2011	Eur Radiol	Retro	33	61.0 ± 7.2	27	CAD	≤1 day	HR > 70 bpm	Siemens SOMATOM Definition Dual-source CT; Software Wizard, Siemens Healthcare; slice thickness 6 mm; slice gap 0 mm; 20 phases	Siemens 1.5 T Sonata; Software Argus Siemens; True FISP cine sequences; slice thickness 6 mm; slice gap 0 mm; unk
Fuchs A	2012	J Cardiovasc Comput Tomoqr	Pro	51	61 ± 10	45	MI	Average 9 days	unk	Toshiba 64-slice MDCT; Software Vitrea fX 3.1;slice thickness 2 mm; slice gap 2 mm; 20 phases	Siemens Avanto 1.5 T; Soft- ware Argus; SSFP sequences; slice thickness 8 mm; slice gap 0 mm; 25 phases
Maffei Eri	2012	Eur Radiol	Pro	79	58 ± 17	46	CAD	≤7 days	HR > 65 bpm	Siemens 64-slice spiral CT; Software Siemens Argus; slice thickness 8 mm; slice gap 2 mm; 20 phases	Philips 1.5 T Achieva; Software Siemens Argus; b-SSFP sequences; slice thickness 8 mm; slice gap 2 mm; 30 phases
Thomas Elgeti	2004	J Comput Assist Tomogr	Pro	27	58.7 ± 9.7	23	CAD 15 DCM 12	≤7 days	unk	GE Evolution C-150XP Scanner; Software unk; slice thickness 8 mm; slice gap 4 mm every second slice; unk	Siemens 1.5 T; Software magneton vision numaris 3; GE sequences; slice thickness 10 mm; slice gap 0 mm; unk
Plumhans C	2008	Am J Roentgenol	Pro	38	55.0 ± 8.8	25	Suspected CAD	≤1 day	HR > 70 bpm	Philips 64-MDCT; Software Siemens Argus; slice thickness 5 mm; slice gap 0 mm; 20 phases	Philips 1.5 T Gyroscan Intera; Software Siemens Argus; balanced fast-field echo sequences; slice thickness 5 mm; slice gap 0 mm; 50 phases
Lembcke A	2005	Ann Thorac Surg	Pro	25	54.9 ± 13.7	18	RHF normal	≤7 days	unk	Toshiba 8 or 16-detector-row CT; Software unk; slice thickness 5 mm;slice gap unk; 20 phases	Siemens 1.5 T Magneton; Software unk; two dimensional fast low angle shot Cine sequences; slice thickness 5 mm; slice gap 0 mm; unk

Pro, prospective; *Retro*, retrospective; *TOF*, tetralogy of Fallot; *CAD*, coronary artery disease; *HCM*, hypertrophic cardiomyopathy; *MR*, mitral regurgitation; *COPD*, chronic obstructive pulmonary disease; *CP*, cor pulmonale; *PAD*, pulmonary artery disease; *PH*, pulmonary hypertension; *CHF*, congestive heart failure; *PAH*, primary arterial hypertension; *CHD*, congenital heart disease; *DCM*, dilated cardiomyopathy; *HHD*, hypertensive heart disease; *RHF*, right heart failure; *RMS*, rheumatic mitral stenosis; *MI*, myocardial infarction

Table 2 Pooled results and heterogeneity of the 4 indexes in our meta-analysis

	EDV		ESV		RVEF		SV	
	Overall results	Heterogeneity (%)	Overall results	Heterogeneity (%)	Overall results	Heterogeneity (%)	Overall results	Heterogeneity (%)
19 studies	3.30 (0.92, 5.67)	40.0	4.87 (2.60, 7.14)	24.7	− 1.65 (− 3.02, − 0.28)	0.0	1.45 (− 1.06, 3.95)	0.0
16 studies	1.04 (− 2.59, 4.67)	0.0	1.22 (1.50, 3.95)	0.0	− 0.65 (− 2.60, 1.29)	0.0	− 0.37 (− 3.64, 2.90)	0.0
3 studies	16.05 (10.59, 21.51)	5.4	13.02 (8.94, 17.10)	0.0	− 2.63 (− 4.56, − 0.70)	0.0	4.01 (0.12, 7.90)	0.0
Subgroup A	4.30 (− 6.19, 14.78)	0.0	3.28 (− 4.53, 11.09)	0.0	− 1.60 (− 6.39, 3.18)	0.0	0.02 (− 9.97, 10.0)	0.0
Subgroup B	0.60 (− 3.27, 4.47)	0.0	0.67 (− 2.49, 3.83)	0.0	− 0.17 (− 2.52, 2.18)	0.0	− 0.47 (− 3.98, 3.05)	0.0

Discussion

This systematic review and meta-analysis demonstrated that CT is a reliable substitute for MRI. Compared to corresponding MRI results, EDV and ESV were overestimated by CT with disk summation, whereas RVEF and SV were slightly underestimated. This is in accordance with previous meta-analysis reporting CT applications for functional analysis of the left ventricle [13]. Our results indicate that CT achieves acceptable accuracy for assessing cardiac function. Accuracy can be further improved by increasing the number of scanning slices or detectors, which enhances spatial and temporal resolution.

A previous meta-analysis reported that 3D echocardiography was more accurate than 2D echocardiography for the evaluation of cardiac function, but still with non-negligible deviation as compared with MRI [38]. Thus, 3D echocardiography is not reliable enough for cardiac function assessment. This inaccuracy may be caused by the intrinsic disadvantage of echocardiography, limitation of RV's special morphology on echocardiography, and the 3D reconstruction algorithm. In our research, the accuracy of the pooled RVF indexes was limited by the inclusion of three studies that measured RVF with a 3D reconstruction algorithm. When these studies were included, very prominent heterogeneity was observed and the MD between corresponding CT and MRI indexes increased. The overall outcome of the 3 studies was not satisfactory, as the pooled MD was larger, and the LOA was wider than that for the 16 studies that used disk summation. Different methods were also applied in MRI. The studies of Yamasaki et al and Fuchs et al employed 3D reconstruction in CT assessment but slice summation in MRI assessment, while Sugeng et al used 3D reconstruction for both CT and MRI [25, 33, 36]. Whether this difference in measurement method influences the consistency between CT and MRI (and led to unsatisfactory results for the 3 studies) requires further study. In the included studies, only the study by Fuchs et al applied automatic segmentation. Automatic segmentation of cardiac function used a variety of segmentation methods, such as threshold, pixel classification, cardiac atlases, and statistical shape models. Automatic segmentation allows accurate and rapid assessment of cardiac function and could be applied in 2D or 3D [39]. Although many papers about automatic segmentation of RV by CT have been reported, its accuracy in the evaluation of RV as compared with MRI is still unknown.

Several technical factors may account for the small disparities between CT and MRI. Unsatisfactory temporary resolution (TR) of CT is currently a major problem. In our meta-analysis, the TR of MRI ranged from 15 to 50 ms compared with 50–210 ms for CT. Excellent TR

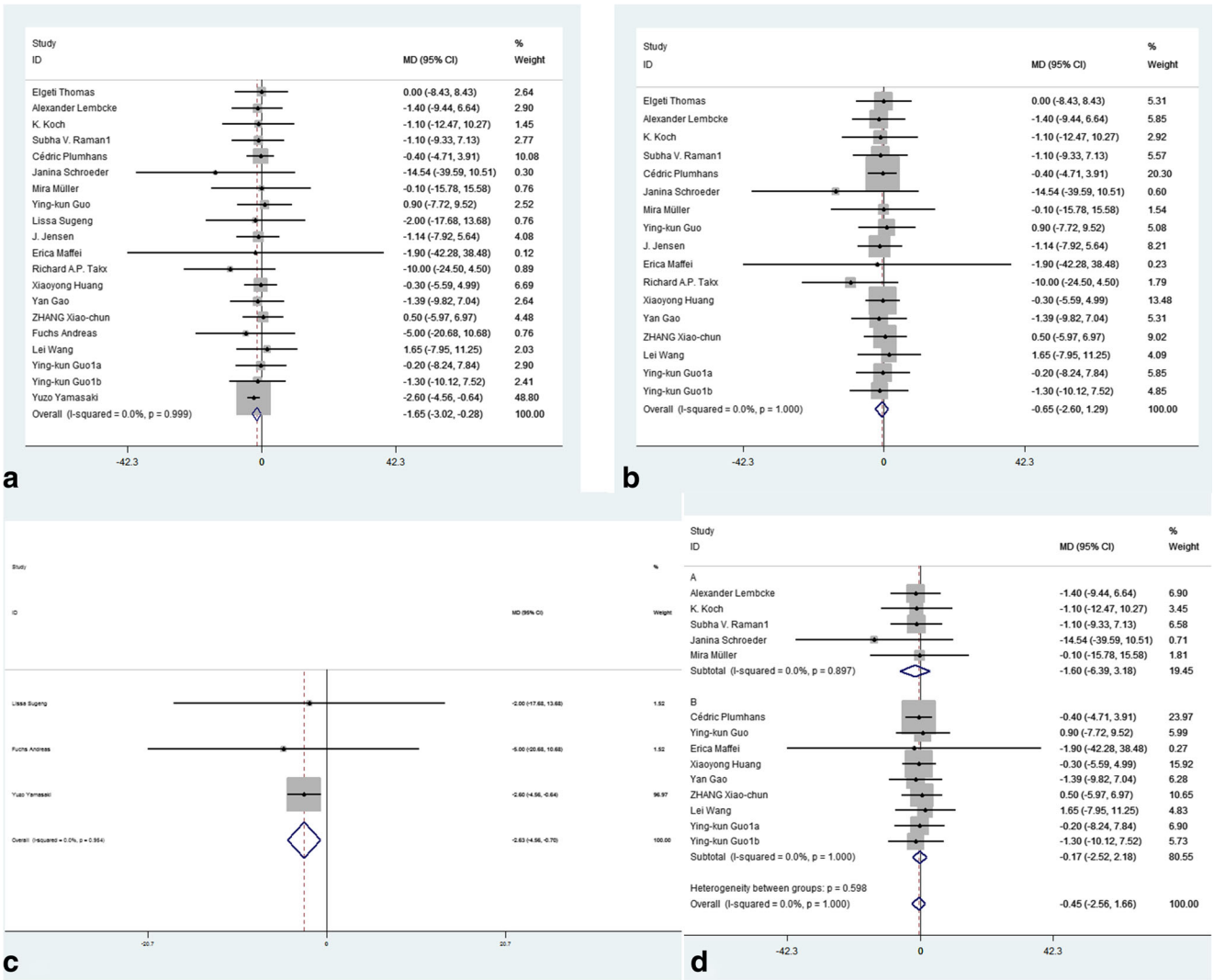

Fig. 3 **a** Forest plots of RVEF in all 19 studies; **b** forest plots of RVEF in 16 studies using disk summation; **c** forest plots of RVEF in 3 studies using 3D reconstruction; **d** forest plots of RVEF in subgroups based on slices of CT scanner of the 16 studies as defined before

helps to reduce motion artifacts caused by heartbeat and respiration, which makes it easier to define the endocardium. The calculation of ventricular volume by the summation of slices was performed by multiplying the slice areas by the slice thickness and adding all the slices. Consequently, unified slice thickness and slice gap contributed to maintain good consistency between CT and MRI. However, only one-half of the 16 studies that used slice summation applied the same slice thickness and slice gap. This was an important factor that increased the difference between CT and MRI. As EDV and ESV were defined as the cardiac phases with the largest and the smallest areas visually, the cardiac phases had to be the same to ensure acceptable agreement of end systole and end diastole between CT and MRI. Nevertheless, none of the 19 included studies implied that the heart phases between the two modalities were the same. Another possible source of discrepancy was the contrast agent injection protocol of CT. Different contrast agent injection protocols would have an impact on the enhancement of the RV, which was important for accurately tracing the RV contour and separating the cavity from the myocardium. Our included studies performed CT scanning based on the scanning protocol of CT coronary angiography. However, the details of contrast agent injection protocol were different (see Table 3 in Online supplementary material). Compared with the studies of CT coronary angiography [40], our included studies used a much higher volume of contrast agent. Thus, the enhancement duration of the RV was prolonged. To obtain the best enhancement of RV, some small factors, such as contrast agent volume, delay time, or multi-phase injection, might need to be optimized on the basis of the

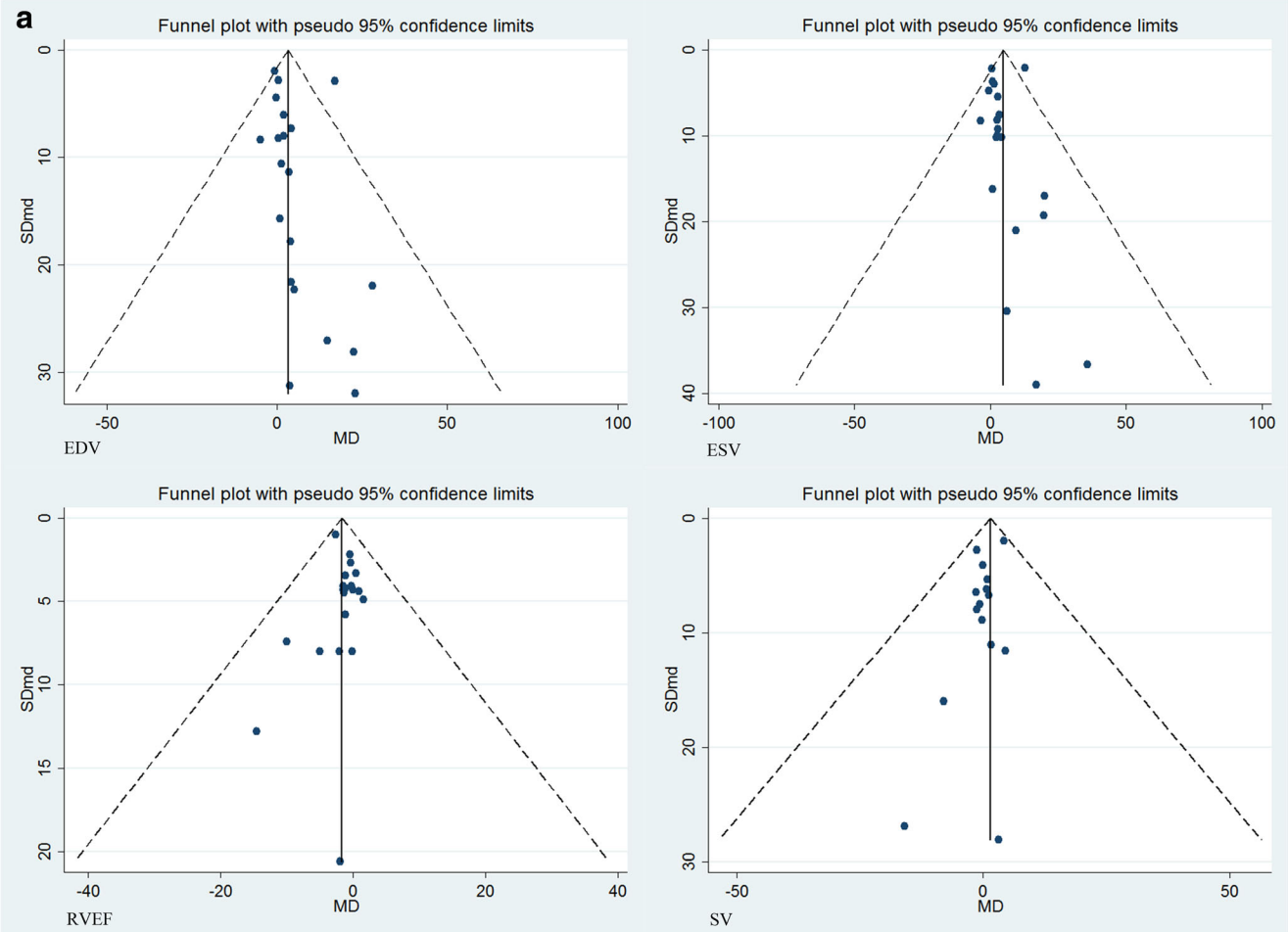

Fig. 4 **a** Funnel plots of EDV, ESV, RVEF and SV of 19 studies; **b** funnel plots of EDV, ESV, RVEF and SV of 16 studies using disk summation

contrast method of CT coronary angiography. Burghard et al applied a biphasic injection protocol to reduce streak-flow artifacts, and only two of his patients suffered this type of artifacts [41]. However, there was no consensus on the injection protocol. In addition, most of the included studies regularly injected saline after injecting iodine contrast agent, which might reduce the density of the RV and lead to an inaccurate definition of the endocardium. Additionally, the region of interest might be set in the RV or pulmonary artery, and CT attenuation of the RV should be measured to ensure maximum enhancement of the RV. However, CT attenuation and image quality were measured only in the study by Lembcke et al [34]. Alternatively, the effect of magnetic field strength on the final results was negligible because the imaging quality of 1.5 Tesla was equal to that of the 3.0 Tesla (i.e., there is no substantial reduction in signal-to-noise ratio using a 1.5 T) [42]. Furthermore, only one study used a 3.0-Tesla system in our meta-analysis [36].

Physiological factors may have also reduced the consistency between modalities. Cardiac function can be affected by the negative inotropic and chronotropic actions of β-blockers. Five of our included studies administered β-blockers before CT examination [20, 21, 28, 31, 32]. The effect of β-blockers on cardiac function should also be considered according to the time interval between CT and MRI as the half-life of metoprolol (approximately 5 h) is much shorter than the delay between CT and MRI (1–7 days) [43]. Additionally, some of the recruited patients may be taking β-blockers at the time of examination. Despite a possible influence of β-blockers, the consistency between the two modalities was good in our study and may further improve by eliminating the potential effects of β-blockers. A 256-slice CT has wider detector coverage and faster rotation time (up to 270 ms) than other systems. These technical improvements reduce examination time without sacrificing image quality and may be particularly suitable for patients with higher heart rates [44]. Another physiological factor that may have contributed to the differences between

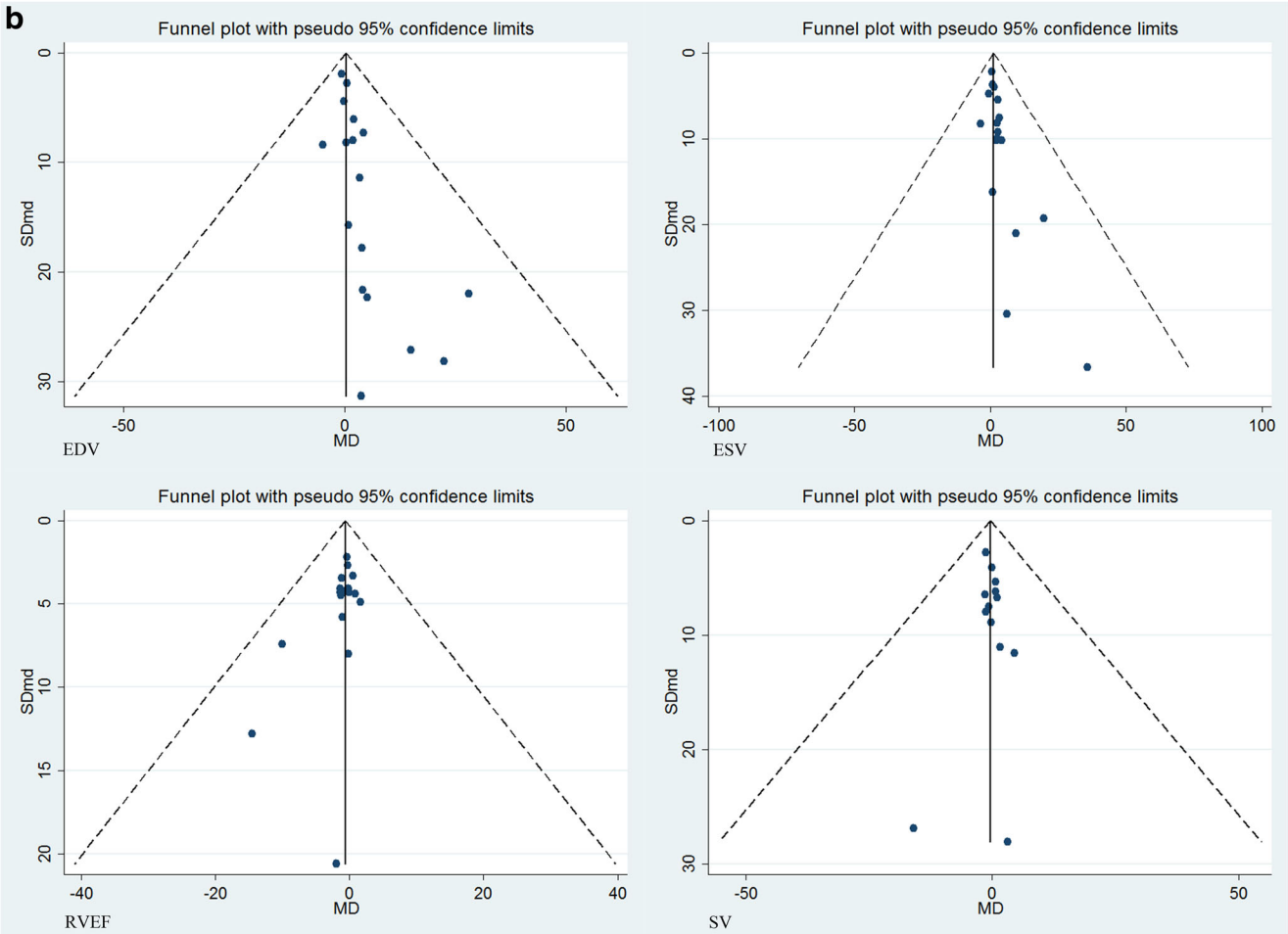

Fig. 4 (continued)

CT and MRI is respiration status during scanning. Both CT and MRI require breath-holding during cardiac imaging, but breath-holding during different phases (end expiration or end inspiration) during the two examinations would affect venous return and influence cardiac function. Inspiration would decrease venous return and thus cardiac volume. In contrast, expiration can increase cardiac volume.

Due to radiation exposure and administration of iodinated contrast agent, CT is not employed for cardiac function analysis in daily practice. Eleven studies reported radiation doses (0.5 to 20 mSv) in this meta-analysis [20, 22, 24–27, 30, 31, 35–37]. However, in addition to the many possibilities to reduce the dose, the benefit/risk balance can be influenced by some advantages of CT: CT can assess RV function and coronary artery at the same time; CT detects lung changes, which helps determine the etiology of RV dysfunction caused by pulmonary diseases. A single examination of the entire chest could assess coronary artery disease, pulmonary embolism, and acute aortic syndrome. Another advantage of CT is that the examination can be completed with only one breath-hold, which is especially suitable for patients who cannot endure long examination times in the supine position with repeated breath-holding.

Limitations

There are two main limitations in our study. First, although the limitation of the interval between CT and MRI has been included in the criteria, intervals of some studies are still relatively long (the longest interval was 19 days [25]). Another limitation is that we discuss the accuracy of CT in the assessment of RVF in general without subgroup analysis according to disease classification. Further studies should focus on RVF assessment with CT in specific diseases.

Conclusion

In conclusion, RVF, as measured by CT, was very similar to that evaluated with MRI, which is the current reference standard for cardiac function measurements. CT is a reliable

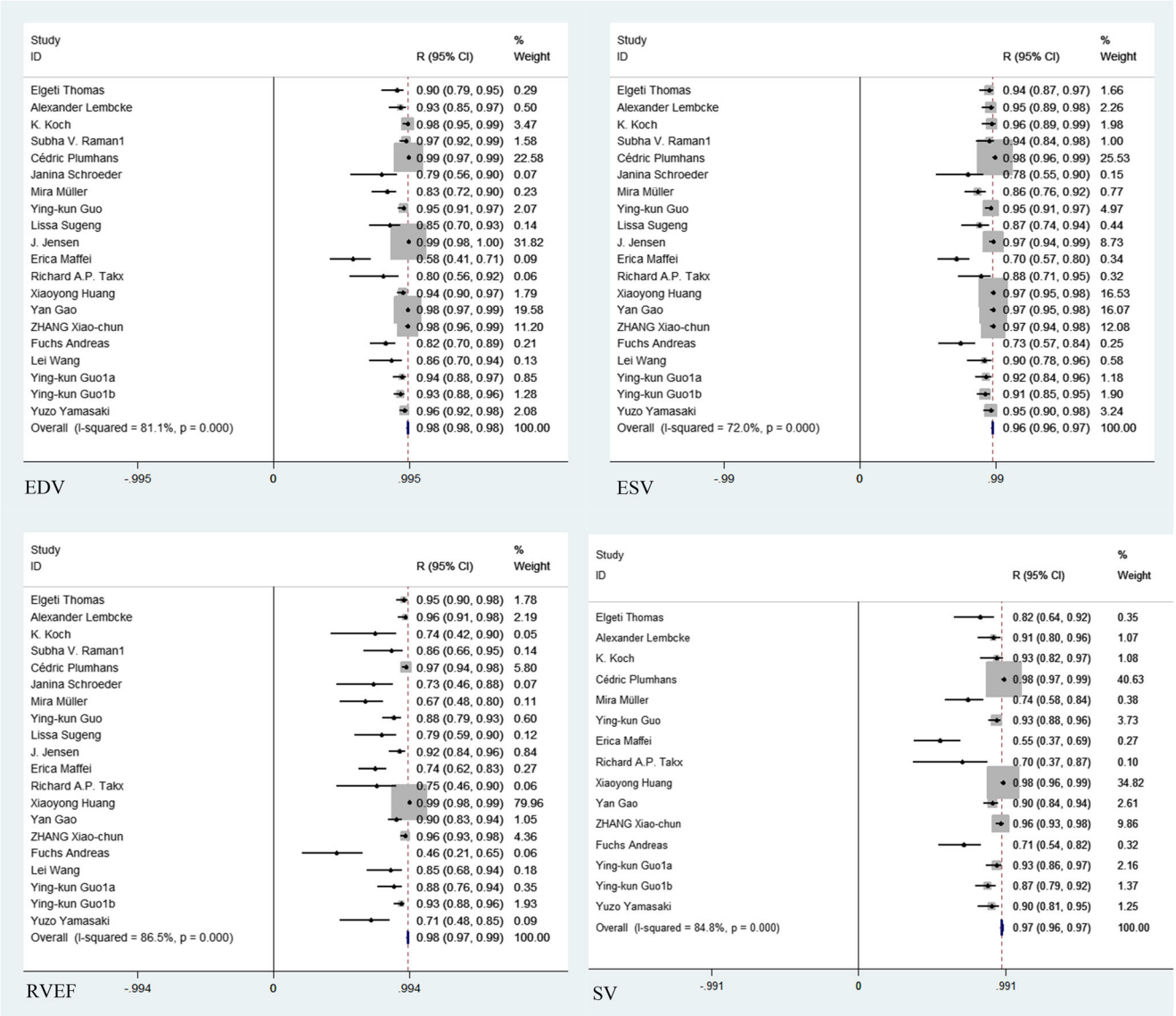

Fig. 5 Forest plots of correlation coefficient of EDV, ESV, RVEF and SV measured by CT and MRI in all included studies

alternative when MRI is not possible. We anticipate that continuous technical advances in CT will offer a more accurate assessment of RVF altogether with a lower radiation dose.

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Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Ying-kun Guo.

Conflict of interest The authors report no conflicts of interest.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was not required for this study because it is a meta-analysis.

Ethical approval Institutional Review Board approval was not required because of the meta-analysis study design.

Study subjects or cohorts overlap Study subjects and cohorts have been reported previously as detailed in the methods and results as well as reference.

Methodology
• Performed at one institution

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