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The Role of 2, 4, and 5-dimensional Cardiac Flow MRI for Evaluation of Valvulopathies: A Literature Review

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ABSTRACT

Aim: Two-dimensional phase-contrast magnetic resonance imaging (2D flow MRI) and its multidimensional alternatives, 4D and 5D flow MRI, measure blood flow in the heart and great vessels. While 2D flow MRI is the standard technique, it has limitations regarding need for precise image plane prescribing and long scan time. In contrast, 4D and 5D flow MRI acquire 3D volumes, enabling retrospective assessment of all vessels. This review evaluates these three techniques for quantification of blood flow of the aortic and pulmonary valves in congenital heart disease.

Methods: A systematic literature search was conducted in August 2024 using the PUBMED database, including articles comparing 2D, 4D, and 5D flow MRI.

Results: Fifteen articles comparing 2D and 4D, one comparing 2D and 5D and three articles comparing 4D and 5D flow MRI were included. No study compared all three techniques. 2D, 4D and 5D flow MRI demonstrated a good agreement for flow quantification. 4D flow MRI, however, tends to present a better accuracy and internal consistency than 2D flow MRI for determination of peak velocities and flow in stenotic lesions, particularly when comparing velocities to echocardiography. 4D and 5D flow MRI are associated with shorter scan times than 2D flow MRI.

Conclusions: 4D and 5D flow MRI appear to offer promising alternatives to 2D flow MRI with the advantage of reduced scan times. Larger and prospective studies including echocardiography are needed to evaluate the potential of 4D and 5D to replace 2D flow MRI for flow quantification and peak velocity determination.

1 | Introduction

Two-dimensional phase-contrast magnetic resonance imaging (2D flow MRI) was first proposed in the 1980s [1] and, to date, is a valuable tool to aid in the diagnosis and monitoring of cardiovascular disease, along with echocardiography and invasive catheterization [2].

The 2D flow MRI technique allows measurement of blood velocity in one direction, perpendicular to the image plane

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; 4D, four-dimensional; 5D, five-dimensional; AA, ascending aorta; AV, aortic valve; BAV, bicuspid aortic valve-; DA, descending aorta; HV, healthy volunteers; ICC, intra-class correlation coefficients; IVC, inferior vena cava; LPA, left pulmonary artery; MPA, main pulmonary artery; MRI, magnetic resonance imaging; nRMSE, normalized root mean square error; PR, pulmonary regurgitation; PV, pulmonary valve; *r*, Pearson's Correlation Coefficient; RF, regurgitation fraction; RPA, right pulmonary artery; bSSFP, balanced steady state free precession; SVC, superior vena cava; TAV, tricuspid aortic valve; TAVI, transcatheter aortic valve implantation; TTE, transthoracic echocardiography; TV, tricuspid valve.

predefined by a cardiac MRI expert [1–4]. To image the volume of a vessel of interest, multiple 2D flow MRI planes can be acquired consecutively and perpendicularly along the vessel [2].

This technique is easy to use and well-established in the clinical setting, but has several limitations:

1. Prolonged breath holding: 2D flow MRI is sensitive to respiratory movements, which is why image acquisition is often performed at the end of expiration [5]. Therefore, the patient must hold their breath during image acquisition, which can be very challenging [1, 3, 6]. Alternatively, free-breathing acquisition can be performed requiring averaging to account for respiratory movement [7].
2. Long and unpredictable scan times: 2D flow MRI images in different locations require multiple acquisitions, resulting in long examination times. The scan time depends on the number of images acquired, prolonging importantly the scan time [6].
3. Sedation of children: This technique requires sedation of young children, in whom breath holding is often impossible [6, 8, 9].
4. Errors in establishing MRI planes: Each examination requires the presence at the scanner of a highly trained cardiac MRI technologist to determine scan planes and acquisition parameters [6, 8]. Errors in the choice of planes (e.g., not perpendicular to the vessel) often force a repeat examination [3]. If the examination is already finished and the patient has left the scanner, it is impossible to correct the image plane [3].
5. Unidirectional measurement: Blood flow through the cavities of the heart and great vessels is pulsatile and is subject to multidirectional variations. 2D flow MRI measures velocity only through one plane and is unable to optimally analyze velocity patterns in cardiac cavities or eccentric flow due to for example, stenosis or regurgitation [2, 3].

As an alternative to 2D flow MRI, the 3D (three-dimensional) flow MRI technique, also known as four-dimensional (4D) flow MRI (volumetric coverage plus 3D velocity encoding), was introduced [2–4]. It allows quantification of velocities in three directions in a 3D volume and retrospective quantification of blood flow in multiple vessels using a single imaging sequence [2–4].

This technique also allows the acquisition independently of breathing (free-breathing) [4]. This increases the patient comfort during scanning and diminishes, or even prevents, the need for general anesthesia in pediatric patients [8].

To account for the respiratory motion of the heart, the so-called navigator technique is used. Navigators are placed on the hepatic dome assuming that the diaphragmatic motion corresponds to the movement of the heart during the respiratory cycle [2, 10, 11]. Usually, only the end-expiratory images are used for the reconstruction of the 3D volume [10, 11]. Limitations of this approach include a low acceptance rate, often less than 40%, potential issues with misplaced navigators resulting in prolonged examination times, unreliable adaptive windowing techniques in the case of significant respiratory motion variations, and suboptimal accuracy in motion detection due to a fixed correlation factor not accounting for interpatient variability and being influenced by hysteretic effects and temporal delays [11]. These issues can result in extended acquisition times [11, 12]. Thanks to the development of acceleration techniques such as compressed sensing, k-t methods, radial and spiral acquisitions, which have enabled shorter scan times, 4D flow MRI has seen a significant increase in clinical use since 2010 [1, 2, 4].

To overcome the limitations of 4D flow, several extensions of 4D flow MRI have been developed over the last years under the name 5D flow MRI (five-dimensional MRI) [12, 13].

The five dimensions include the three spatial dimensions (x-y-z) plus two distinct temporal dimensions representing the cardiac and respiratory phases [14].

This modern imaging technique allows simultaneous detection of blood flow and cardiac anatomy and acquires images during the entire respiratory cycle ("free running"), without excluding the inspiratory phase and without the need for diaphragmatic respiratory navigation [13, 15]. After image acquisition, the information is divided into intervals of the corresponding respiratory cycle (end-expiratory and end-inspiratory images), and respiration-dependent blood flow measurements can be analyzed (respiratory motion resolved flow datasets) [13]. 5D flow MRI is therefore independent of the patient's respiratory efficiency, allowing for predictable scan times [12, 13].

An additional advantage of free running 5D flow MRI is its independence from ECG detection and triggering: it is no longer necessary to record cardiac electrical activity by attaching electrodes to the patient [15]. Instead, detection of cardiac and respiratory motion can be achieved by processing specific data acquired during acquisition, using the so-called self-gating (SG) technique [15].

There is an increasing number of studies comparing 2D and 4D flow MRI, however, there are currently a limited number of studies comparing 2D and 4D with 5D flow MRI, and there are no studies comparing all the three modalities [4]. The aim of this literature review is to investigate the existing knowledge regarding the comparison, advantages, and disadvantages of these techniques with a particular focus on the aortic and pulmonary valves (AV and PV) in healthy volunteers (HV) and in patients with specific congenital heart disease (CHD) (repaired tetralogy of Fallot [rTOF], d-transposition of the great vessels [d-TGA]).

2 | Methods

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta Analysis (PRISMA) 2013 guidelines [16]. The research question was defined based on the PICOS model: participants; interventions; comparators; outcomes; study designs [16]. To ensure that this was the first systematic review on the topic, we searched the Cochrane database for systematic reviews in January 2023.

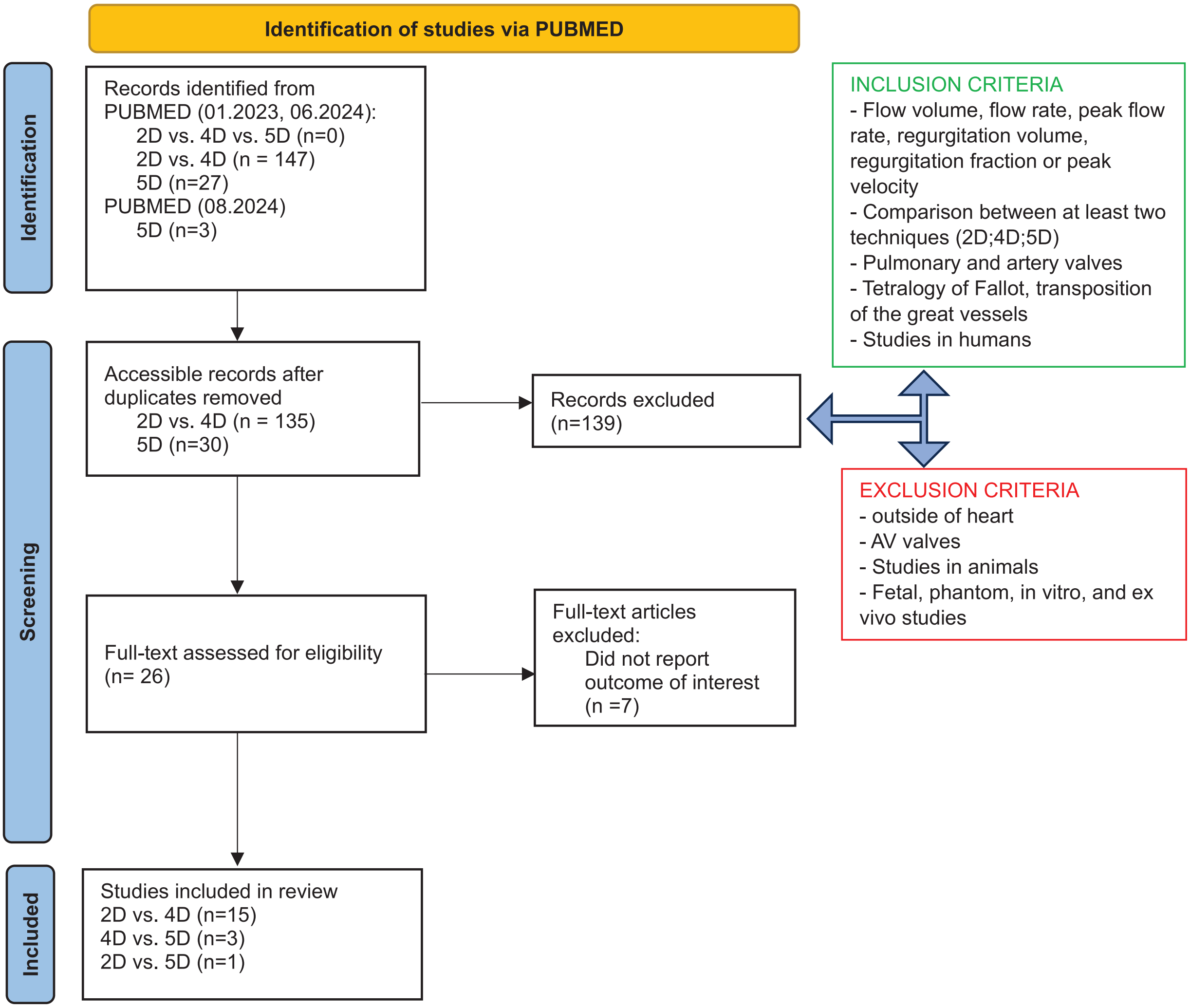

FIGURE 1 | Flow diagram showing the article selection and exclusion process.

2.1 | Search strategy

A systematic literature search was performed in January 2023 and updated in August 2024 using the PUBMED database. The focus was on articles comparing 2D, 4D and 5D flow MRI techniques for assessing cardiac blood flow. The search was limited to English-language articles published since 2010, marking the period when 4D flow MRI gained clinical importance [1, 2, 3]. Articles were screened according to specific eligibility criteria, as illustrated in Figure 1.

The search for 2D and 4D flow MRI comparison yielded 147 results, which were reduced to 135 accessible articles. These were further screened by titles and abstract to identify the most relevant studies.

The 5D flow MRI search, completed in August 2024, identified 30 results. After screening, only four studies were included, as the remaining articles did not compare techniques and only focused on 5D flow MRI.

For inclusion in this review, articles had to measure one or more of the following parameters: flow volume (forward, backward, net flow volume, stroke volume), flow rate, peak flow rate, regurgitation volume or regurgitation fraction (RF), peak velocity. Additional criteria included comparison of two of the following techniques: 2D flow MRI, 4D flow MRI and 5D flow MRI; and studies conducted in humans.

The search was specifically targeted on articles focusing on evaluation of aortic and pulmonary valvulopathies as well as CHD, particularly rTOF and d-TGA.

After screening, the selected articles were reviewed.

Fifteen papers were finally included for comparison between 2D and 4D flow MRI, along with four articles addressing 5D flow MRI.

2.2 | Data Extraction

The following methodological information was collected for each article (see Table 1): the number and type of participants (patients or HV), the mean age of participants, the study design (prospective, retrospective), the techniques compared, and the

TABLE 1 | Methodological information.

First author (year)	Reference number	Number and age of participants (y)	Design	Type of flow	Vessels investi-gated	Flow parameters	Results
Nordmeyer et al. (2013)	[18]	7 HV (34), 18 patients (26)	Prospective	2D flow MRI, 4D flow MRI, echo	AA, PV, MPA	Stroke volume, peak velocity	Peak velocity significantly higher with 4D ($p = 0.025$), but not different from echo ($p > 0.05$). Stroke volume not significantly different.
Rose et al. (2016)	[19]	51 patients (14)	Prospective	2D flow MRI, 4D flow MRI, echo	AA, aortic arch, DA	Peak velocity	Higher peak velocity with 4D than with 2D ($p < 0.001$, $r = 0.87$, $p < 0.001$). Strong correlation and agreement between 4D and echo ($r = 0.79$, $p < 0.001$, mean difference 0.02 ± 0.57 m/s).
Alvarez et al. (2020)	[20]	34 patients (58)	Retrospective	2D flow MRI, 4D flow MRI	AA	Forward flow, regurgitation flow, regurgitation fraction	Excellent correlation between 2D and 4D: Forward flow volume $r = 0.826$, $p < 0001$, regurgitation volume $r = 0.866$, $p < 0001$ and RF $r = 0.761$, $p < 0001$, no statistically significant differences.
Hautanen et al. (2023)	[21]	83 patients (53.7)	Prospective	2D flow MRI, 4D flow MRI	Aortic root, midtubular AA	Peak velocity, peak flow rate, regurgitation fraction	2D–4D: $r = 0.58$–0.90. 4D provides significantly higher peak velocities in the tubular AA ($p < 0.001$). In the aortic root, peak velocities and peak flow rate significantly higher in the 4D TV group ($p < 0.001$), but in the 4D BV group non-significantly lower values ($p = 0.6$). 4D RF lower in both locations in both groups ($p < 0.001$).
Rooijakkers et al. (2024)	[5]	21 patients (80)	Prospective	2D flow MRI, 4D flow MRI	AV	Paravalvular regurgitation volume	RF measured with 4D had a good correlation with 2D flow ($r = 0.74$, $p < 0.001$). Bland Altman analysis; mean bias of 0.3% ± 5.4%.

(Continues)

TABLE 1 | (Continued)

First author (year)	Reference number	Number and age of participants (y)	Design	Type of flow	Vessels investigated	Flow parameters	Results
Gerhardt et al. (2024)	[22]	31 patients (31)	Retrospective	2D flow MRI, 4D flow MRI	AV, AA, sinotubular junction	Regurgitation flow, net forward volumes	Aortic regurgitation at the valve: mean difference 2D to 4D −2.9%, $r^2 = 0.7$. Net forward flow at the aortic valve by 4D flow correlated closer with main pulmonary artery than did 2D flow.
Van der Hulst et al. (2010)	[25]	19 HV (14.1), 25 patients (13.1)	Prospective	2D flow MRI, 4D flow MRI	PV, TV	Forward flow, regurgitation flow volume	Good correlation between 2D and 4D: Forward flow volume: $r = 0.87$, $p < 0.01$; backward flow volume: $r = 0.97$, $p < 0.01$. 4D superior to 2D for assessment of tricuspid flow.
Hsiao et al. (2012)	[26]	29 patients (8)	Retrospective	2D flow MRI, 4D flow MRI	AA, MPA	Ventricular volume, peak velocity, stroke volume	Good agreement between 2D and 4D for aortic and pulmonary flow rates ($r = 0.90$; $r^2 = 0.82$, mean difference 12%).
Jacobs et al. (2020)	[6]	34 patients (15.6)	Retrospective	2D flow MRI, 4D flow MRI	AA, MPA	Net flow, forward flow and ventricular volumes	For 4D higher correlation pulmonary-aortic net flow volume ($r = 0.87$) and lowest mean difference (3.5 ± 9.4 mL/beat). Forward pulmonary flow volume and stroke volume 4D: $r = 0.66$–0.81, $p < 0.001$; 2D: $r = 0.81$–0.84, $p < 0.001$, no significant difference. Ejection fraction 2D–4D: $r = 0.60$–0.75. Scan time 4D 9 min, 2D 71 min, $p < 0.001$.
Isorni et al. (2020)	[27]	60 patients (18.2)	Retrospective	2D flow MRI, 4D flow MRI	AA, MPA	Net flow, forward flow, backward flow, regurgitation fraction	Strong correlation between 2D and 4D: Pulmonary RF (mean 27% ± 17%, $r = 0.81$, $p < 0.001$), pulmonary net flow rate (mean 4.6 ± 1.6 L/min, $r = 0.82$, $p < 0.001$), pulmonary forward flow rate (mean 6.6 ± 2.3 L/min, $r = 0.90$, $p < 0.001$), pulmonary backward flow rate (mean 2.0 ± 1.7 L/min, $r = 0.92$, $p < 0.001$), aortic valve net flow rate (mean 4.4 ± 1.5, $r = 0.80$, $p < 0.001$). Correlation pulmonary and aortic net flow rate 4D mean 4.6 ± 1.2 L/min, $r = 0.89$, $p < 0.001$ vs. 2D mean 4.4 ± 1.1 L/min, $r = 0.71$, $p < 0.001$.

(Continues)

TABLE 1 | (Continued)

First author (year)	Reference number	Number and age of participants (y)	Design	Type of flow	Vessels investi-gated	Flow parameters	Results
Yao et al. (2021)	[23]	30 patients (6.3)	Retrospective	2D flow MRI, 4D flow MRI	AA, MPA	Net flow, forward flow and ventricular volumetry	Good correlations 2D–4D ($r > 0.60$, $p < 0.001$) and good agreement on Bland Altman analysis. Scan time of 4D shorter than 2D (8.10 ± 2.25 vs. 34.66 ± 7.41 min, $p < 0.001$).
Soulat et al. (2023)	[28]	30 patients	Prospective	2D flow MRI, 4D flow MRI	PV	Regurgitation volume, regurgitation fraction	Net flow volume significantly higher with 4D than with 2D ($p < 0.0001$). Regurgitation volume and RF lower with 4D ($p < 0.0001$). Regurgitation volume: $r = 0.90$, mean difference −14 ± 12.5 mL; RF: $r = 0.72$, mean difference −15% ± 13%; all $p < 0.0001$). Better correlations between Rvol estimates and right ventricle end-diastolic volume decrease after PVR with 4D.
Jarvis et al. (2016)	[29]	19 patients (13)	Prospective	2D flow MRI, 4D flow MRI, echo	AA, MPA, RPA, LPA	Peak velocity	Higher peak velocities with 4D in the AA ($p = 0.003$), MPA ($p = 0.002$) and RPA ($p = 0.005$), but not in the LPA ($p = 0.200$). No difference in peak velocity between 4D and echo ($p > 0.46$). Bland Altman analysis shows for 4D higher peak velocity than 2D: mean difference from 0.14 m/s to 0.31 m/s.
Van Wijk et al. (2019)	[31]	81 patients (20.6)	Prospective	2D flow MRI, 4D flow MRI, echo	AA	Stroke volume, regurgitation fraction	4D higher RF than 2D (8.6% ± 4.9% vs. 6.3% ± 7.2%, $p = 0.09$). Good agreement stroke volume 4D–2D (ICC = 0.77, $p = 0.20$), with underestimation by 2D.
Warmerdam et al. (2024)	[30]	39 patients (20)	Prospective	2D flow MRI, 4D flow MRI, echo	MPA, RPA, LPA	Stroke volume, peak velocity	Higher peak velocities with 4D in MPA, RPA, LPA ($p < 0.001$). For stroke volumes good agreement between 2D and 4D.
Walheim et al. (2019)	[12]	9 HV (30)	Retrospective	4D flow MRI, 5D flow MRI	AA	Peak velocity, peak flow	5D: higher peak velocities (3.1% ± 4.4%) and lower peak flow (−2.4% ± 6.9%). 4D–5D: nRMSE between velocities 8.9% ± 2.1%. 5D scan time: 4 min, 4D scan time 17.8 ± 3.7 min.

(Continues)

TABLE 1 | (Continued)

First author (year)	Reference number	Number and age of participants (y)	Design	Type of flow	Vessels investi-gated	Flow parameters	Results
Ma et al. (2020)	[13]	20 patients (49)	Prospective	4D flow MRI, 5D flow MRI	AA, aortic arch, DA, SVC, IVC	Net flow, peak flow, peak velocity	5D overestimated net flow volume (up to 26%) and peak velocity (up to 12%) in the AA and underestimated them (<12%) in the arch and DA ($p < 0.05$ for all). 5D scan time 7.65 ± 0.35 min vs. 9.88 ± 3.17 min of 4D ($p < 0.01$).
Falcão et al. (2021)	[32]	15 HV (23–34), 9 patients (13–55)	Prospective	4D flow MRI, 5D flow MRI	AA, DA	Net flow, peak flow, peak velocity	HV show significant differences between 5D and 4D (for 5D PT: net flow of DA, peak flow rate of arch and DA, peak velocity of DA; for 5D SG: net flow of DA, peak flow rate of aortic root, arch and DA, peak velocity of arch and DA; $p < 0.05$). Differences also in patients (net flow of DA for 5D SG, peak velocity of arch and DA for both 5D SG and PT; $p < 0.05$). Bland Altman HV: net flow volume bias 4.8 ± 31.6 mL for 5D flow PT vs. 4D. Peak flow rate: Bland Altman bias of 6.2 ± 35.0 mL/s for 5D vs. 4D. Overall, 5D underestimated these measurements compared with 4D (main differences in arch and DA)
Weiss et al. (2024)	[33]	10 HV (39.7), 19 patients (14).	Prospective	2D flow MRI, 5D flow MRI	AA, MPA, IVC, SVC	Net flow, peak flow	Good agreement with no significant differences in net flow volume and peak flow measurements derived from 5D and 2D ($p < 0.001$).

Abbreviations: AA, ascending aorta; AV, aortic valve; BV, bicuspid aortic valves; DA, descending aorta; HV, healthy volunteers; ICC, intra-class correlation coefficients; IVC, inferior vena cava; LPA, left pulmonary artery; MPA, main pulmonary artery; nRMSE, normalized root mean square error; PT, pilot tone; PV, pulmonary valve; RF, regurgitant fraction; RPA, right pulmonary artery; SG, self-gating; SVC, superior vena cava; TV, tricuspid valve;, y, years; 2D, 2D flow MRI; 4D, 4D flow MRI; 5D, 5D flow MRI.

TABLE 2 | Flow parameters.

Parameter	Parameter Unit
Forward, backward, and net flow volume	mL or L/heartbeat
Stroke volume	mL or L/heartbeat
Flow rate	mL or L/s or min
Peak flow rate	mL or L/s or min
Regurgitation volume	mL or L/heartbeat
Regurgitation fraction	%
Peak velocity	cm or m/s

specific anatomical structures evaluated (vessels or heart valves). The flow parameters that were extracted are presented in Table 2.

2.3 | Classification of Studies

The selected studies were divided into two main groups for analysing: 2D versus 4D flow MRI and 2D or 4D versus 5D flow MRI.

Studies that compared 2D flow MRI and 4D flow MRI were further classified into subgroups, including AV, rTOF, and d-TGA. Studies that compared 2D flow MRI and 4D flow MRI included standard and accelerated 4D flow MRI. For each comparison, it was specified whether an accelerated method was used.

2.4 | Classification of Quality

The quality of the included studies was assessed using the Critical Appraisal Skills Programme (CASP) systematic review checklist, which consists of 10 questions designed to evaluate the quality of the studies [17].

2.5 | Classification of Comparability

Agreement between flow determination was qualified as follows: Data from Bland Altman comparisons were summarized as bias (mean difference between the two techniques) and limits of agreement or relative difference expressed in percentage of the mean value or standard deviation.

Correlations were denoted by the Pearson's correlation coefficient "r" or the square of the correlation coefficient r^2 (coefficient of determination). The following correlation were considered: $r < 0.3$ poor; $r = 0.3$–0.5 low; $r = 0.5$–0.7 moderate; $r = 0.7$–0.9 high; $r > 0.9$ very high.

2.6 | Quantitative Assessment

Due to the heterogeneity of the studies, missing data, and the diversity of parameters investigated, a generalized meta-analysis could not be performed. Therefore, we conducted a narrative review, analyzing the similarities and differences among the studies.

3 | Results

All results are summarised in Table 1.

3.1 | Comparison 2D and 4D Flow MRI; Aortic Valve

Six studies were identified comparing 2D flow MRI with 4D flow MRI, focusing on the evaluation of aortic valvulopathies. In 2013, Nordmeyer et al. [18] analyzed peak velocity and stroke volume in the ascending aorta (AA) and main pulmonary artery (MPA) in 18 patients with aortic or PV stenosis, as well as 7 HV. They found that in patients, the peak velocity through the stenotic valves was significantly higher with 4D flow MRI than with 2D flow MRI ($p = 0.025$). Additionally, 2D flow MRI underestimated peak velocity compared to transthoracic echocardiography (TTE), whereas 4D flow MRI provided more accurate results (TTE vs. 2D flow MRI: 2.8 vs. 2.4 m/s, $p < 0.01$; TTE vs. 4D flow MRI: 2.8 vs. 2.7 m/s, $p > 0.05$). The correlation between 4D flow MRI and TTE was strong ($r = 0.80$ [$p < 0.0001$]). No significant differences in peak velocities were observed between 2D and 4D flow MRI in volunteers ($p > 0.05$). Bland Altman analysis showed good agreement between 2D flow MRI and 4D flow MRI for quantification of stroke volume and peak velocity in both HV and patients (visual assessment of values based on Figure 3 in the article).

Three years later, Rose et al. [19] conducted a study involving 51 patients with bicuspid aortic valve (BAV) and reported similar findings. They observed that peak velocity measured by 4D flow MRI was significantly higher than that measured by 2D flow MRI ($p < 0.001$). Although Bland Altman analysis and correlation showed good agreement of peak velocities measured by both methods (bias 0.35 ± 0.38 m/s, $r = 0.87$, $p < 0.001$), better correlation and agreement were found between 4D flow MRI and TTE than between 2D flow MRI and TTE ($r = 0.79$, $p < 0.001$, mean difference 0.02 ± 0.57 m/s). The authors used systolic velocity maximum intensity projections (MIPs) with 4D flow MRI to improve peak velocity assessment for the evaluation of valve stenosis.

In 2020, Alvarez et al. [20] reported in 34 patients with aortic valve regurgitation (AR) an excellent correlation between 4D flow MRI and standard 2D flow MRI for assessing aortic forward flow volume ($r = 0.826$, $p < 0.001$), regurgitation volume ($r = 0.866$, $p < 0.001$), and RF ($r = 0.761$, $p < 0.001$), with no significant differences observed.

In 2023, Hautanen et al. [21] studied 83 subjects with BAV or TAV, analyzing peak flow rate, RF, and peak velocity at two levels: the aortic root and mid-tubular aorta. They found that the correlation between 2D and 4D flow MRI ranged from moderate to high ($r = 0.58$–0.90). 4D flow MRI yielded again significantly higher peak velocities than 2D flow MRI in the tubular aorta ($p < 0.001$). At the level of the aortic root, peak velocities and peak flow rates were significantly higher in the TAV group using 4D flow MRI ($p < 0.001$), but not different in the BAV group

($p = 0.6$). RFs derived from 4D flow MRI were lower at both locations in both groups ($p < 0.001$).

In 2024, Rooijakkers et al. [5] analyzed 21 patients after transcatheter aortic valve implantation (TAVI) and reported good correlation between 2D and 4D flow MRI for assessing paravalvular RF ($r = 0.74$, $p < 0.001$). The Bland Altman analysis showed no significant bias, with a mean bias of 0.3% ± 5.4%. The study demonstrated excellent intra- and inter-observer reproducibility for 2D flow MRI (0.97 and 0.99, respectively) and good reproducibility for 4D flow MRI (0.92 and 0.90).

In the same year, Gerhardt et al. [22] investigated 31 patients with congenital AV disease using 2D and 4D flow MRI to measure flow parameters (antegrade flow volume, net forward flow volume, and aortic regurgitation) through the AV, with MPA measurements as a reference. They found that the more distant from the valve the flow was measured, the more the 2D flow MRI tended to overestimate flow volumes compared to the 4D flow MRI. At the AV level, the mean flow difference between 2D and 4D flow MRI was −2.9%, with limits of agreement ranging from 8.7% to 14.3% and $r^2 = 0.7$. The net forward flow at the level of the AV was closer to the measurements of the MPA using 4D flow MRI, indicating better accuracy than 2D flow MRI.

Conclusions: 4D flow MRI yields in general higher peak velocities than 2D flow MRI in patients with aortic valvulopathies like valvular stenosis and regurgitation in both TAV and BAV. These peak velocities appear to better correspond to those obtained by TTE, which is considered the non-invasive gold standard. 2D and 4D flow MRI calculated stroke volumes through the AV show relatively good agreement with a trend to an overestimation by 2D flow MRI. RF appears to correlate well between 2D and 4D flow MRI.

3.2 | Comparison 2D and 4D Flow MRI: Tetralogy of Fallot

After rTOF, patients often develop pulmonary valve regurgitation (PR), which can lead to right ventricular dysfunction [23, 24]. Therefore, PR and right ventricular function need to be monitored, and MRI is considered to be the gold standard for non-invasive follow-up of PR [6, 23, 24].

In 2021, Elsayed et al. [24] published a systematic review on 4D flow MRI in rTOF: identifying 13 articles comparing it with 2D flow MRI and four articles comparing it with TTE. They concluded that 4D flow MRI had good potential in rTOF assessment, particularly when using valve tracking for evaluation of standard flow parameters like stroke volume, peak velocity but also advanced 4D flow parameters such as quantification of intracardiac kinetic energy, and vortex visualization.

Since this review, two papers were published on the comparison of 4D flow MRI and 2D flow MRI in rTOF.

Reviewing the above 13 articles, it was noticed that most of them included a variety of different CHD lesions in addition to rTOF. To focus on rTOF, we considered only the studies including more than 20 rTOF patients and a comparison with 2D flow MRI.

Van der Hulst et al. [25] were probably the first, in 2010, to compare 2D and 4D flow MRI in patients with rTOF. Among 25 patients they found that 4D flow MRI was accurate in assessing PV flow in patients and healthy children compared with 2D flow MRI (Pearson's correlation coefficient forward flow volume: $r = 0.87$, $p < 0.01$; backward flow volume: $r = 0.97$, $p < 0.01$). Interestingly, 2D and 4D flow MRI derived pulmonary forward flow differed significantly to forward flow derived by planimetry. The authors also evaluated tricuspid flow, finding that 4D flow MRI was superior to 2D flow MRI in assessing it.

In 2012, Hsiao et al. [26] compared ejection fractions and flow rates derived from 4D flow MRI with those obtained using 2D flow MRI and cine-derived ejection fraction (balanced steady-state free-precession [bSSFP]) in 29 patients with rTOF. They found good agreement between 2D and 4D flow MRI for aortic and pulmonary flow rates ($r = 0.90$; $r^2 = 0.82$, mean difference 12%). Excluding patients with PR, ventricular and stroke volumes derived from 4D flow MRI were more consistent than those obtained with 2D flow MRI and SSFP.

Jacobs et al. [6] compared the two techniques in 2020 in 34 patients with rTOF and found good agreement between the two techniques. Using 4D flow MRI, pulmonary net flow volume presented the strongest correlation ($r = 0.87$) and the lowest mean difference (3.5 ± 9.4 mL) compared with net flow volume at the AV level which was used for evaluation of internal consistency. Forward pulmonary flow volume and stroke volume had moderate-strong correlation (4D flow MRI: $r = 0.66$–0.81, $p < 0.001$; 2D flow MRI: $r = 0.81$–0.84, $p < 0.001$) with no significant differences for correlation coefficients or mean differences between techniques. Ejection fraction had a moderate correlation ($r = 0.60$–0.75) between 4D flow MRI and 2D flow MRI. The time advantage of 4D flow MRI over 2D flow MRI was also accentuated in this study (9 vs. 71 min, $p < 0.001$).

In 2020, Isorni et al. [27], who conducted the largest retrospective study with 60 participants, found that for patients with moderate PR fraction (mean 27 ± 17), there was a strong correlation between 2D flow MRI and 4D flow MRI for several parameters. They reported the following correlations: PR fraction ($r = 0.81$, $p < 0.001$), pulmonary net flow ($r = 0.82$, $p < 0.001$), pulmonary forward flow ($r = 0.90$, $p < 0.001$), pulmonary backward flow ($r = 0.92$, $p < 0.001$), and AV net flow ($r = 0.80$, $p < 0.001$). The Bland Altman analyses showed narrow limits of agreement for these measurements. Similar to the above-cited studies, the correlation between pulmonary and aortic net flow rate was higher with 4D flow MRI than with 2D flow MRI ($r = 0.89$, $p < 0.001$ vs. $r = 0.71$, $p < 0.001$).

Yao et al. [23] analyzed in 2021 a pediatric population of 30 patients with rTOF and found a moderate to good correlations between 2D flow MRI and 4D flow MRI for quantification of net flow, forward flow, peak velocity, and RF in the aorta and MPA ($r > 0.60$, $p < 0.001$) and good agreement in Bland Altman analysis. As in the study of Jacobs et al., the scan time of 4D flow MRI was shorter than that of 2D flow MRI (8.10 ± 2.25 vs. 34.66 ± 7.41 min, $p < 0.001$).

In 2023, Soulat et al. [28] studied pulmonary flow in 30 adult patients with PR, including 22 with rTOF. Net flow volume was significantly higher with 4D flow MRI than with 2D flow MRI ($p < 0.0001$), while regurgitation volume and RF were lower ($p < 0.0001$). Regurgitation volume and RF measured by 2D flow MRI and 4D flow MRI correlated well, but only with moderate agreement and wide limits of agreement (regurgitation volume: $r = 0.90$, mean difference −14 ± 12.5 mL; RF: $r = 0.72$, mean difference −15% ± 13%; all $p < 0.0001$). 4D flow MRI derived regurgitation volume correlated better to the decrease of RV size after surgical repair of PR than those derived by 2D flow MRI.

Conclusions: A relatively large number of studies reported good correlation and agreement between 2D flow MRI and 4D flow MRI in assessing pulmonary forward and backward flow, peak velocity and RF in patients with rTOF. When comparing internal consistency, 4D flow MRI appears to be superior to 2D flow MRI and is associated with a reduced scan time.

3.3 | Comparison 2D and 4D Flow MRI: Transposition of the Great Vessels

One of the most important complications in adult d-TGA patients treated with arterial switch operation (ASO) is right ventricular outflow tract (RVOT) stenosis [29, 30]. Peak velocity measurements obtained by MRI allow the assessment of the significance of stenosis [29].

Jarvis et al. [29] measured peak velocities in 19 patients with d-TGA after ASO and compared 4D flow MRI with 2D flow MRI. They found higher peak velocities with 4D flow MRI in the AA ($p = 0.003$), MPA ($p = 0.002$) and right pulmonary artery (RPA) ($p = 0.005$), but not in the left pulmonary artery (LPA) ($p = 0.200$). Bland Altman analysis showed that the peak velocity measurements from 4D flow MRI were higher than those from 2D flow MRI, with a mean difference of 0.14 m/s to 0.31 m/s. Peak velocities did not differ between 2D and 4D flow MRI and Doppler echocardiography, respectively.

A further complication after ASO, aortic regurgitation (AR), was evaluated in 2019 by Van Wijk et al. [31], who compared 2D flow MRI with 4D flow MRI in 81 patients with significant AR. 4D flow MRI showed a trend towards a higher RF than 2D flow MRI (8.6% ± 4.9% vs. 6.3% ± 7.2%, $p = 0.09$), although this difference was not statistically significant. Stroke volume assessment showed moderate agreement between 4D and 2D flow MRI (ICC = 0.77, $p = 0.20$), with an underestimation by 2D flow MRI.

In 2024, Warmerdam et al. [30] analyzed 39 patients after ASO and compared peak velocity and stroke volume in MPA, RPA, and LPA between 4D flow MRI, 2D flow MRI and TTE. They found significantly higher peak velocities with 4D flow MRI than with 2D flow MRI in the MPA, RPA, and LPA ($p < 0.001$ for all). There was a good agreement and no significant differences between the peak velocities measured by 4D flow MRI and TTE. Stroke volumes measured by 4D flow MRI were not significantly different from 2D flow MRI.

Conclusions: In d-TGA patients, 4D flow MRI generally provides higher peak velocities compared to 2D flow MRI, with likely better agreement to TTE. The results suggest better accuracy of 4D flow MRI compared to 2D flow MRI for the detection of stenosis. 4D flow MRI showed good agreement but higher values than 2D flow MRI for the assessment of AR in patients after ASO. However, the number of studies on this topic is limited, and the sample sizes are insufficient to draw definitive conclusions on the role of 4D flow MRI in ASO.

3.4 | Comparison 2D and 4D to 5D Flow MRI

As mentioned in the introduction, the data acquisition time with 4D flow MRI depends on the subject's breathing pattern, limiting the method's applicability in the clinical setting [12]. As an alternative, the recent 5D flow MRI technique provides resolved cardiac and respiratory motion assessment of velocity maps and turbulent kinetic energy at fixed scan times (independent of respiratory behavior or cardiac cycle variations) [12, 13].

Due to the recent introduction of the 5D flow MRI technique, the available literature is limited. This is reflected in the absence of studies comparing 2D with 4D and 5D flow MRI.

However, three articles compared flow analysis between 4D flow MRI and 5D flow MRI, and one article published in 2024 compared the 5D technique with standard 2D flow MRI.

In 2019, Walheim et al. [12] analyzed blood flow in the aorta in 9 HV and found good agreement for 5D flow MRI compared with 4D flow MRI, with higher peak velocities assessed with 5D flow MRI (3.1% ± 4.4%) and lower peak flow (−2.4% ± 6.9%). The nRMSE (normalized root mean square error) between the velocity magnitudes obtained with 5D flow MRI and the 4D flow MRI reference was 8.9% ± 2.1%. A fixed 5D flow MRI protocol of 4 min was used, independent of individual breathing patterns, whereas the standard 4D flow MRI scan times varied and averaged 17.8 ± 3.7 min (about 4.5 times longer).

Ma et al. [13] in 2020 studied 20 patients with aortic disease and found a moderate agreement between 4D flow MRI and 5D flow MRI: 5D flow MRI overestimated net flow volume (up to 26%) and peak velocity (up to 12%) in the AA and underestimated them (<12%) in the arch and descending aorta (DA) ($p < 0.05$ for all). The 5D flow MRI had shorter examination times than the 4D flow MRI: on average 7.65 ± 0.35 min versus 9.88 ± 3.17 min ($p < 0.01$). The authors also demonstrated the influence of respiration on flow in the vena cava.

In 2021, Falcão et al. [32] compared the recently developed pilot tone (PT) 5D flow MRI with the previously established self-gating (SG) 5D flow MRI, presented by Ma et al. in 2020, as well as with 4D flow MRI in a study involving 15 healthy adults and 9 CHD patients. PT navigation is a technique for monitoring physiological motions in CMR and enables respiratory and cardiac motion resolved 5D flow MRI. While quantification of flow and peak velocities did not differ between both 5D flow MRI techniques, there was a consistent underestimation of net flow at the level of the aortic arch and DA of flow measured with both 5D flow MRI techniques compared with 4D flow MRI.

In 2024, Weiss et al. [33] published a study comparing respiratory resolved 5D flow MRI with real-time 2D flow MRI. They evaluated net and peak flow in four vessels (AA, MPA, superior, and inferior vena cava) in 10 HV and 19 CHD patients. The results showed good agreement between the two techniques, with no significant differences in net flow volume and peak flow measurements derived from 5D flow MRI and 2D flow MRI ($p < 0.001$). Similar to the study by Ma et al., the authors investigated the impact of respiration on venous flow [13].

Conclusions: Studies comparing 5D flow MRI with 2D or 4D flow MRI are scarce and include only a small number of participants. However, some conclusions can be drawn: 5D flow MRI allows predictive and shorter scan times compared to 4D flow MRI (4–8 min). It tends to overestimate net flow and peak velocity in the AA while underestimating these parameters in the aortic arch and DA compared to 4D flow MRI. Additionally, 5D flow MRI has the advantage to investigate the effects of respiration and cardiac motion on cardiovascular flow and hemodynamics.

4 | Discussion

Based on our analysis, we can conclude that in most studies, 4D flow MRI provides similar results to standard 2D flow MRI. There is strong agreement between the two techniques, with 4D flow MRI being associated with shorter scan time and a free breathing approach, which renders the exam more comfortable for the patient. While 2D flow MRI remains the established reference technique, it has several limitations, particularly in evaluating complex flow. Our analysis suggests that 4D flow MRI shows better agreement with TTE for determining velocities in stenotic valves [18, 19, 30]. An explanation for this finding is probably that 4D flow MRI, with its ability to encode velocity in three dimensions, also depicts excentric flow, which is typically present in turbulent flow, such as in valvular stenosis [29, 30]. In contrast, 2D flow MRI only measures flow in a single direction, resulting in lower maximum velocities [29, 30]. For this reason, 4D flow MRI appears to be superior to 2D flow MRI particularly in patients with stenotic valulopathies as, for example, in BAV .

For patients with rTOF, the available studies and data suggest that 4D flow MRI could replace 2D flow MRI in assessing blood flow. There is strong agreement between 2D and 4D flow MRI in evaluating pulmonary flow parameters, with 4D flow MRI demonstrating higher internal consistency and a better correlation with the reduction of RV volume after surgical correction.

In d-TGA after ASO, however, larger studies are still needed before definitive conclusions can be drawn. The results of existing studies align with the observations described above regarding the evaluation of aortic and pulmonary pathologies.

Free running 5D flow MRI offers short and predictable scan times without requiring ECG triggering and respiratory detection. Early studies suggested a trend toward overestimating net flow and peak velocity in the AA and underestimating these parameters in the arch and DA; however, this was not confirmed in the most recent study.

Current studies seem to be focused on defining the fastest MRI technique to assess flow and go beyond comparing new accelerated methods to the standard 2D flow MRI. A large-scale, multicenter study evaluating and comparing all three techniques is urgently needed. The results of such a study would significantly enhance knowledge in this field and facilitate future practical applications.

5 | Limitations

Based on the current literature, no definitive conclusions on the comparability of standard 2D flow MRI with 4D flow MRI and the new 5D flow MRI sequence can be reached for several reasons:

- The number of available studies on the comparison between 2D and 4D flow MRI is relatively limited and even fewer, namely only four studies on the comparison of 2D and 4D with 5D flow MRI are available.
- Patient populations are very heterogenous. The population size in most of the studies is small, with the largest sample consisting of 83 participants [21]. Consequently, the generalization of results to broader populations is limited.
- Many studies have a retrospective study design.
- In addition, the nature of systematic reviews allows only existing literature to be used, and the presence of bias and limitations in the included studies affects the reliability of the review.
- Despite numerous developments on 5D flow MRI, few studies have attempted to compare cardiac flow measurement between 5D flow MRI and 2D and 4D flow MRI. No investigation has been published so far comparing the three modalities.

6 | Conclusion

The objective of this literature review was to investigate the similarities and differences between 2D, 4D, and 5D flow MRI techniques for assessing cardiac blood flow, with a particular focus on CHD patients. The review shows that only a limited number of studies are available. However, despite these limitations, accelerated 4D flow MRI and 5D flow MRI sequences show significant potential to replace standard 2D flow MRI, as they allow easy, rapid, and reliable determination of flow in all vessels. There is an urgent need for prospective studies to validate these new techniques against the well-established non-invasive reference method for flow determination, 2D flow MRI. However, echocardiography should be integrated in these studies for the validation of peak flow velocities.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article, as no new data were created or analyzed in this study.

References

1. A. Azarine, P. Garçon, A. Stansal, et al., "Four-Dimensional Flow MRI: Principles and Cardiovascular Applications," *Radiographics* 39, no. 3 (2019): 632–648, https://doi.org/10.1148/rg.2019180091.

2. M. Gabbour, S. Schnell, K. Jarvis, J. D. Robinson, M. Markl, and C. K. Rigsby, "4-D Flow Magnetic Resonance Imaging: Blood Flow Quantification Compared to 2-D Phase-Contrast Magnetic Resonance Imaging and Doppler Echocardiography," *Pediatric Radiology* 45, no. 6 (2015): 804–813, https://doi.org/10.1007/s00247-014.

3. E. Bollache, P. van Ooij, A. Powell, J. Carr, M. Markl, and A. J. Barker, "Comparison of 4D Flow and 2D Velocity-Encoded Phase Contrast MRI Sequences for the Evaluation of Aortic Hemodynamics," *The International Journal of Cardiovascular Imaging* 32, no. 10 (2016): 1529–1541, https://doi.org/10.1007/s10554-016-0938-5.

4. C. M. Doyle, J. Orr, J. P. Greenwood, S. Plein, C. Tsoumpas, and M. M. Bissell, "Four-Dimensional Flow Magnetic Resonance Imaging in the Assessment of Blood Flow in the Heart and Great Vessels: A Systematic Review," *Journal of Magnetic Resonance Imaging* 55, no. 5 (2022): 1301–1321, https://doi.org/10.1002/jmri.27874.

5. M. J. P. Rooijakkers, S. El Messaoudi, N. A. Stens, et al., "Assessment of Paravalvular Regurgitation After Transcatheter Aortic Valve Replacement Using 2D Multi-Venc and 4D Flow CMR," *European Heart Journal—Cardiovascular Imaging* 25, no. 7 (2024): 929–936, https://doi.org/10.1093/ehjci/jeae035.

6. K. G. Jacobs, F. P. Chan, J. Y. Cheng, S. S. Vasanawala, and S. A. Maskatia, "4D flow vs 2D Cardiac MRI for the Evaluation of Pulmonary Regurgitation and Ventricular Volume in Repaired Tetralogy of Fallot: A Retrospective Case Control Study," *The International Journal of Cardiovascular Imaging* 36, no. 4 (2020): 657–669, https://doi.org/10.1007/s10554-019-01751-1.

7. F. Xiong, T. Emrich, U. J. Schoepf, et al., "Highly Accelerated Free-Breathing Real-time 2D Flow Imaging Using Compressed Sensing and Shared Velocity Encoding," *European Radiology* 34, no. 3 (2024): 1692–1703, https://doi.org/10.1007/s00330-023-10157-6.

8. P. Sjöberg, E. Hedström, K. Fricke, et al., "Comparison of 2D and 4D Flow MRI in Neonates Without General Anesthesia," *Journal of Magnetic Resonance Imaging* 57, no. 1 (2023): 71–82, https://doi.org/10.1002/jmri.28303.

9. H. R. Panayiotou, L. K. Mills, D. A. Broadbent, et al., "Comprehensive Neonatal Cardiac, Feed and Wrap, Non-contrast, Non-sedated, Free-breathing Compressed Sensing 4D Flow MRI Assessment," *Journal of Magnetic Resonance Imaging* 57, no. 3 (2023): 789–799.

10. M. H. Moghari, R. J. van der Geest, M. Brighenti, and A. J. Powell, "Cardiac Magnetic Resonance Using Fused 3D Cine and 4D Flow Sequences: Validation of Ventricular and Blood Flow Measurements," *Magnetic Resonance Imaging* 74 (2020): 203–212, https://doi.org/10.1016/j.mri.2020.09.026.

11. D. Piccini, A. Littmann, S. Nielles-Vallespin, and M. O. Zenge, "Respiratory Self-navigation for Whole-heart Bright-blood Coronary MRI: Methods for Robust Isolation and Automatic Segmentation of the Blood Pool," *Magnetic Resonance in Medicine* 68, no. 2 (2012): 571–579, https://doi.org/10.1002/mrm.23247.

12. J. Walheim, H. Dillinger, and S. Kozerke, "Multipoint 5D Flow Cardiovascular Magnetic Resonance—Accelerated Cardiac- and Respiratory-Motion Resolved Mapping of Mean and Turbulent Velocities," *Journal of Cardiovascular Magnetic Resonance* 21, no. 1 (2019): 42, https://doi.org/10.1186/s12968-019-0549-0.

13. L. E. Ma, J. Yerly, D. Piccini, et al., "5D Flow MRI: A Fully Self-Gated, Free-Running Framework for Cardiac and Respiratory Motion-Resolved 3D Hemodynamics," *Radiology: Cardiothoracic Imaging* 2, no. 6 (2020): e200219, https://doi.org/10.1148/ryct.2020200219. Erratum in: Radiol Cardiothorac Imaging. 2021 Jun 24;3(3):e219001. PMID: 33385164; PMCID: PMC7755133.

14. L. Feng, S. Coppo, D. Piccini, et al., "5D Whole-Heart Sparse MRI," *Magnetic Resonance in Medicine* 79, no. 2 (2018): 826–838, https://doi.org/10.1002/mrm.26745.

15. L. Di Sopra, D. Piccini, S. Coppo, M. Stuber, and J. Yerly, "An Automated Approach to Fully Self-gated Free-running Cardiac and Respiratory Motion-Resolved 5D Whole-Heart MRI," *Magnetic Resonance in Medicine* 82, no. 6 (2019): 2118–2132, https://doi.org/10.1002/mrm.27898.

16. E. M. Beller, P. P. Glasziou, D. G. Altman, et al., "PRISMA for Abstracts: Reporting Systematic Reviews in Journal and Conference Abstracts," *Plos Medicine* 10, no. 4 (2013): e1001419, https://doi.org/10.1371/journal.pmed.1001419.

17. Critical Appraisal Skills Programme. CASP checklists (2022), https://casp-uk.net/casp-tools-checklists/.

18. S. Nordmeyer, E. Riesenkampff, D. Messroghli, et al., "Four-dimensional Velocity-Encoded Magnetic Resonance Imaging Improves Blood Flow Quantification in Patients With Complex Accelerated Flow," *Journal of Magnetic Resonance Imaging* 37, no. 1 (2013): 208–216, https://doi.org/10.1002/jmri.23793.

19. M. J. Rose, K. Jarvis, V. Chowdhary, et al., "Efficient Method for Volumetric Assessment of Peak Blood Flow Velocity Using 4D Flow MRI," *Journal of Magnetic Resonance Imaging* 44, no. 6 (2016): 1673–1682, https://doi.org/10.1002/jmri.25305.

20. A. Alvarez, V. Martinez, G. Pizarro, M. Recio, and J. Á. Cabrera, "Clinical Use of 4D Flow MRI for Quantification of Aortic Regurgitation," *Open Heart* 7, no. 1 (2020): e001158, https://doi.org/10.1136/openhrt-2019-001158.

21. S. Hautanen, T. Kiljander, T. Korpela, et al., "4D Flow Versus 2D Phase Contrast MRI in Populations With Bi- and Tricuspid Aortic Valves," *In Vivo (Athens, Greece)* 37, no. 1 (2023): 88–98, https://doi.org/10.21873/invivo.13057.

22. P. Gerhardt, N. Shehu, I. Ferrari, et al., "Quantifying Aortic Valve Regurgitation in Patients With Congenital Aortic Valve Disease by 2D and 4D Flow Magnetic Resonance Analysis," *International Journal of Cardiology* 408 (2024): 132084, https://doi.org/10.1016/j.ijcard.2024.132084.

23. X. Yao, L. Hu, Y. Peng, et al., "Right and Left Ventricular Function and Flow Quantification in Pediatric Patients With Repaired Tetralogy of Fallot Using Four-dimensional Flow Magnetic Resonance Imaging," *BMC Medical Imaging* 21, no. 1 (2021): 161, https://doi.org/10.1186/s12880-021-00693-2.

24. A. Elsayed, K. Gilbert, M. Scadeng, et al., "Four-Dimensional Flow Cardiovascular Magnetic Resonance in Tetralogy of Fallot: A Ayah Review," *Journal of Cardiovascular Magnetic Resonance* 23 (2021): 59, https://doi.org/10.1186/s12968-021-00745-0.

25. A. E. Van der Hulst, J. J. M. Westenberg, L. J. M. Kroft, et al., "Tetralogy of Fallot: 3D Velocity-Encoded MR Imaging for Evaluation of Right Ventricular Valve Flow and Diastolic Function in Patients After Correction," *Radiology* 256, no. 3 (2010): 724–734, https://doi.org/10.1148/radiol.10092269.

26. A. Hsiao, M. Lustig, M. T. Alley, et al., "Rapid Pediatric Cardiac Assessment of Flow and Ventricular Volume With Compressed Sensing Parallel Imaging Volumetric Cine Phase-Contrast MRI," *American Journal of Roentgenology* 198, no. 3 (2012): W250–W259, https://doi.org/10.2214/AJR.11.6969.

27. M. A. Isorni, D. Martins, N. Ben Moussa, et al., "4D Flow MRI Versus Conventional 2D for Measuring Pulmonary Flow After Tetralogy of Fallot Repair," *International Journal of Cardiology* 300 (2020): 132–136, https://doi.org/10.1016/j.ijcard.2019.10.030.

28. G. Soulat, Y. Alattar, M. Ladouceur, et al., "Discordance Between 2D and 4D Flow in the Assessment of Pulmonary Regurgitation Severity: A Right Ventricular Remodeling Follow-Up Study," *European Radiology* 33, no. 8 (2023): 5455–5464, https://doi.org/10.1007/s00330-023-09502-6.

29. K. Jarvis, M. Vonder, A. J. Barker, et al., "Hemodynamic Evaluation in Patients With Transposition of the Great Arteries After the Arterial

Switch Operation: 4D Flow and 2D Phase Contrast Cardiovascular Magnetic Resonance Compared With Doppler Echocardiography," *Journal of Cardiovascular Magnetic Resonance* 18, no. 1 (2016): 59, https://doi.org/10.1186/s12968-016-0276-8.

30. E. G. Warmerdam, J. J. M. Westenberg, M. Voskuil, et al., "Comparison of Four-Dimensional Flow MRI, Two-Dimensional Phase-Contrast MRI and Echocardiography in Transposition of the Great Arteries," *Pediatric Cardiology* 45, no. 8 (2023): 1627–1635, https://doi.org/10.1007/s00246-023-03238-2.

31. W. H. S. Van Wijk, J. M. P. J. Breur, J. J. M. Westenberg, et al., "Validation of Aortic Valve 4D Flow Analysis and Myocardial Deformation by Cardiovascular Magnetic Resonance in Patients After the Arterial Switch Operation," *Journal of Cardiovascular Magnetic Resonance* 21 (2019): 20.

32. M. B. L. Falcão, L. Di Sopra, L. Ma, et al., "Pilot Tone Navigation for Respiratory and Cardiac Motion-Resolved Free-Running 5D Flow MRI," *Magnetic Resonance in Medicine* 87 (2021): 718–732, https://doi.org/10.1002/mrm.29023.

33. E. K. Weiss, J. Baraboo, C. K. Rigsby, et al., "Respiratory-Resolved 5D Flow MRI: In-Vivo Validation and Respiratory Dependent Flow Changes in Healthy Volunteers and Patients With Congenital Heart Disease," *Journal of Cardiovascular Magnetic Resonance* 26, no. 2 (2024): 101077, https://doi.org/10.1016/j.jocmr.2024.101077.

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