

Three-dimensional, isotropic MRI: a unified approach to quantification and visualization in congenital heart disease

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Abstract

Purpose: Current standards in magnetic resonance imaging of congenital heart disease are based mostly on anisotropic protocols to image both morphology and function. Operator-dependent acquisition planning is typically needed to obtain the desired images. We propose to instead use operator-independent, three-dimensional, isotropic imaging protocols to acquire both morphology and function (cine and flow) of the entire heart in a few standardized acquisitions. Subsequently, due to the isotropic property of the data, any desired imaging plane can be “imaged” offline by interactive planar reformatting and used for qualitative and quantitative diagnostic evaluation. **Materials and methods:** Morphological data was acquired in patients using 3D steady state free precession (SSFP) protocols, and functional data in volunteers using multislice 2D or 3D cine SSFP as well as 3D, three-component phase-contrast velocity mapping with EPI readouts. Tools to integrate morphological and functional offline image evaluation based on interactive planar reformatting, volume rendering, and corresponding quantification tools were implemented and discussed. **Results:** We successfully acquired and integrated morphology and flow and demonstrated potential clinical applications. **Conclusion:** User independent acquisitions of morphological and functional isotropic 3D datasets with real-time, interactive planar reformatting, volume rendering, and integration of morphology and function, have the potential to replace conventional, user dependent, anisotropic 2D imaging in patients with cardiac malformations.

Introduction

Recently introduced MRI sequences are currently setting new standards in imaging cardiovascular morphology and function in congenital heart disease. For morphological visualization, improved black blood imaging [1], steady state free precession (SSFP) sequences [2, 3], and contrast enhanced angiography [4] are recent improvements.

For quantitative functional studies, SSFP sequences are becoming the standard for determining ventricular volumes [5–7] and myocardial masses [7–9]. Quantitative flow information is acquired from various flow sensitive sequences [10, 11] and can be acquired in 3D [12, 13] and even in real-time [14]. However, even after a careful planning process to obtain the desired images, there is a risk that irregular respiration

and patient motion result in images different from what was planned from the overview images. This can lead to additional planning and repeated acquisitions. In the worst case missing imaging planes are not discovered until post-acquisition. Hence, the overall diagnostic value of the examination is reduced or alternatively the patient needs to be called in for a new examination.

To overcome the above-mentioned problems a new concept of morphological scanning of patients with congenital heart disease was introduced in [15]: An isotropic whole-heart 3D SSFP sequence was evaluated, and it was concluded that this single, operator-independent acquisition was sufficient to obtain full morphological diagnoses in adolescents and adults with congenital heart disease. Due to the isotropic property of the data, any desired imaging plane could be reformatted from the acquired volume. In fact, the study showed that all diagnostic work could be performed exclusively by offline real-time planar reformatting, eliminating the risk of missing imaging planes as discussed above. In this paper we elaborate further on this concept of operator-independency and offline imaging by extending the work in [15] to isotropic 3D acquisitions of both morphology and function (cine and flow). The prospect is to demonstrate the clinical potential contained in the integration of such isotropic acquisitions. We will define and apply isotropic protocols and implement the software tools necessary to illustrate and discuss a new imaging strategy in congenital heart disease. Ultimately, the goal is to be able to derive all necessary diagnostic information from a small number of standardized acquisitions. We discuss the benefits of isotropic imaging under two headings, namely (1) interactive planar reformatting and two-dimensional quantification, (2) integration of morphology and function. In the remaining article, flow imaging refers to phase-contrast MRI.

Interactive planar reformatting and two-dimensional quantification

Using isotropic, three-dimensional imaging protocols the entire heart and the great vessels can be

covered in a single, MR-operator independent acquisition and any desired imaging plane can be consequently “imaged” offline by interactive post-processing without loss of resolution. This planar reformatting can be applied to both morphological, cine, and flow data. For three-component flow acquisitions this implies interactive visualization of both through-plane and in-plane velocity components. Quantitative measurements such as distances, areas, and flow rates can be obtained at any time from any such reformatted slice. For accurate and reproducible quantification, the slice of interest can be defined from two orthogonal slices to avoid angulation errors caused by using only single (or non-) angulated slices. Alternatively, a three-dimensional volume rendering can be used as a morphological placeholder to interactively define the desired reformatted slices.

Integration of morphology and function

Thin structures such as the atrial septum and the cardiac valves may be difficult to outline from morphological MR image data alone. Whether, e.g., an atrial septum is intact or deficient can be difficult to determine with certainty. An intracardiac shunt is more likely revealed by a flow acquisition [16, 17]. Looking at an isolated flow acquisition, however, it might be difficult to determine whether the slice position and angulation are indeed the desired. More credibility could potentially be put to the diagnosis if identical slices were available of both morphology and flow. Indeed, by utilizing the proposed real-time reformatting tools to interactively visualize any desired imaging plane from aligned datasets, morphological slices could be integrated with functional information (cardiac motion, blood flow) and thus potentially increase the sensitivity and specificity of the examination. We assume that patients do not move during the entire scanning session. If this is not the case however, some registration of motion correction would be required to align the various datasets.

Materials and methods

MR imaging

A Philips 1.5T Inera scanner with Power Track 6000 gradients, release 9 software, and a 5 element cardiac synergy coil was used to acquire all data-sets. Sensitivity encoding [18] was used for cine and flow imaging with a factor of 1.5–2.0.

A 3D, singlephase SSFP sequence [15] was used to image morphology with 1.6^3 mm^3 – 2.1^3 mm^3 true isotropic voxels using Vector-ECG-triggering [19] and a flip angle of 90° . The acquisition window length was set between 30 ms and 120 ms depending on the heart rate. For adults and adolescents (low heart rate, $n = 40$ patients aged 6–42 years) we recorded in late diastole. For infants and small children (high heart rate, $n = 3$ patients aged 2–4 years) an individual window was determined from an initial cine acquisition showing the right coronary artery [20]. For anesthetized infants and small children no respiratory correction was used. In larger individuals scanning was performed during free breathing using prospective, real-time navigator gating [21] on the right hemidiaphragm (5 mm window). A spectrally selective fat saturation pulse (SPIR) and a T2 preparation pulse [22] were used to increase contrast between the blood pool, fat and muscles. Scan duration was 5–10 min (including navigator inefficiency) for volumes covering the entire heart and vessels from the diaphragm to above the aortic arch in approximately 100–120 sagittal slices.

2D multislice, multiphase, near-isotropic SSFP sequences were used to obtain 40 slices with an in-plane resolution of $2.5 \times 2.5 \text{ mm}^2$ and thickness of 3.5 mm in five breath holds of 25 s each using retrospective ECG-triggering ($n = 3$ volunteers). Scan parameters were: 3.1 ms repetition time (TR), 1.6 ms echo time (TE), 70° flip angle, and 50 ms heart phase intervals.

3D, three-component phase contrast velocity measurements were made using a previously validated navigator gated, 3D hybrid segmented k -space phase-contrast gradient echo technique with EPI readouts [23, 12]. Fifty 3.0^3 mm^3 slices were acquired in approximately

8 min using a 7 mm navigator window ($n = 6$, 3 adult patients and 3 volunteers). Parameters were TE = 3.3 ms, TR = 7.1 ms, 7 EPI readouts, velocity encoding = 150 cm/s for all three orthogonal components of velocity, and 59 ms heart phase interval.

Visualization

Dedicated software to illustrate our concepts was developed in C++ in Linux and run on a commercially available PC with a 1 GHz Intel processor, 512 MB of memory, and a Geforce FX 5900 graphics card (Geforce, Nvidia, USA) with 256 MB texture memory. Parts of the software were subsequently ported to Microsoft Windows (Systematic Software Engineering, Denmark).

Interactive planar reformatting and two-dimensional quantification

Figure 1 shows one example of an interface for offline reformatting of arbitrary slices in an isotropic volume of data. Any desired image is reformatted from two orthogonal planes. The lines defining the intersections of the planes (and hence the planes themselves) can be translated and rotated interactively. The implementation that allows visualization of arbitrary imaging planes was straightforward using 3D texturing hardware. Real-time in-plane and through-plane flow visualization of arbitrarily reformatted slices from three-dimensional, three-component flow volumes was implemented using a dedicated fragment program programmed directly for the graphics card (using Cg, Nvidia, USA). Through-plane flow magnitudes were calculated as the signed magnitudes of each three-component voxel flow vector were projected onto the plane normal. For in-plane flow magnitudes, each flow vector was projected onto a user defined in-plane direction, still in real-time. Thus, flow curves, stroke volumes and absolute flow rates could be calculated from the chosen slices.

Integration of morphology and function

By extracting slice positions and angulations from the scanner for each acquisition, any two acquisitions

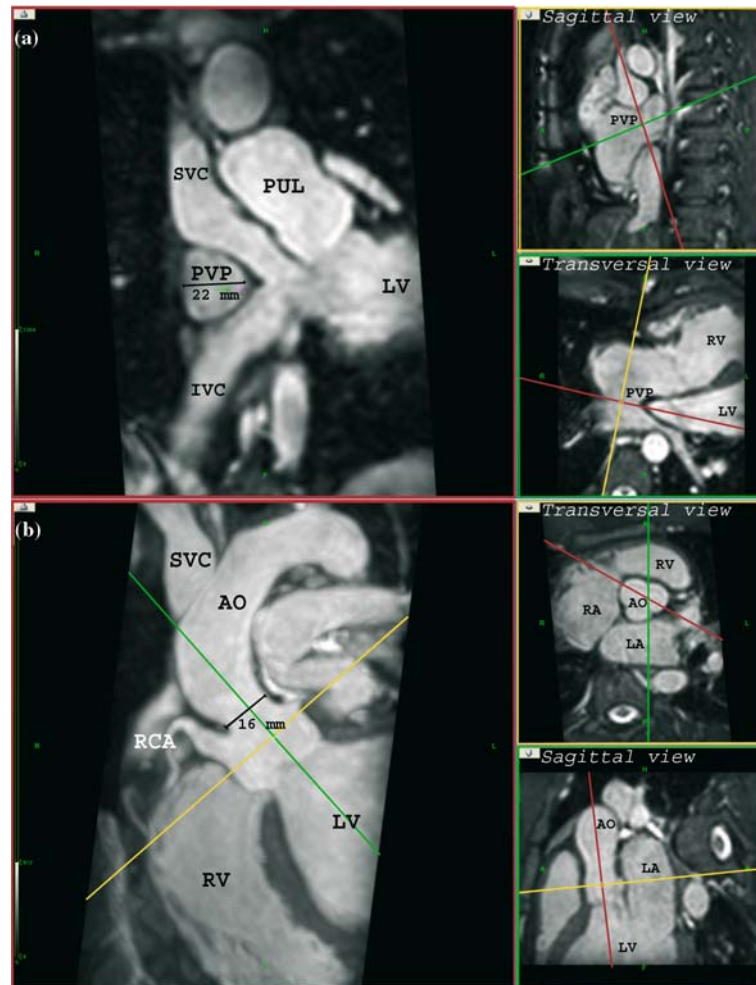


Figure 1. Planar reformatting from orthogonal slices. For each subfigure two orthogonal planes (right) are used to interactively define a planar reformatting (left). The visible intersection lines identifies the intersections of pairs of planes. A line color represents the frame color of the corresponding intersection plane. Together, the two red lines in the orthogonal views span the reformatted image to their left. The orthogonal planes can be defined arbitrarily under the constraint that their normals are always perpendicular. (a) Patient with d-transposition of the great arteries (d-TGA) and Mustard atrial switch. The orthogonal views were defined along the length axis of the pulmonary venous pathway (PVP). Hence, the leftmost reformatting could be planned to appear perpendicular to the PVP and its dimensions measured (22 mm). Also visible is the unobstructed systemic venous pathways from the inferior (IVC) and superior vena cava (SVC) to the left ventricle (LV). (b) Patient with a small supravalvular aortic stenosis caused by an abnormal origin of the right coronary artery (RCA). The stenosis was measured to 16 mm in a reformatted 10 mm maximum intensity projection (MIP). Further abbreviations: AO: aorta, LA: left atrium, RA: right atrium, RV: right ventricle, PUL: pulmonary trunk.

from the same examination could be aligned. This was used to interactively reformat identical slices from morphological and flow examinations. Alternatively, the position and angulation of a previously acquired two-dimensional image could be used to

clip a volume rendering of a three-dimensional acquisition to achieve a morphological localization of the slice – provided that the same respiratory phase was underlying both acquisitions. Volume rendering was implemented according to [24].

Ethics

All patient data were acquired as part of routine clinical examinations. Volunteers were examined after obtaining written informed consent as approved by the local ethical committee on medical research.

Results

Using the described hardware and software it was possible to achieve real-time interactivity (more than 30 frames/s) for interactive planar reformatting, volume rendering, and combinations of the two techniques on the acquired 3D volumes of morphology and function.

Interactive planar reformatting and two-dimensional quantification

Clinically relevant examples of 2D images acquired by interactive reformatting of 3D morphological datasets are shown in Figure 1. In a patient with d-transposition of the great arteries and Mustard atrial switch, the unobstructed systemic venous and pulmonary venous pathways are visualized by planar reformatting (Figure 1a). In a patient with supravalvular aortic stenosis caused by an abnormal origin of the right coronary artery, a 10 mm maximum intensity projection is reformatted to determine the degree of stenosis (Figure 1b). In general, quantification of e.g. degrees of stenoses, septal defect sizes, and ventricular and atrial out-flow tract diameters was possible after choosing the optimal plane. An example of a volume rendering guided planar reformatting from a patient with a previous coarctation repair is seen in Figure 2. The course of the aortic arch is clearly depicted in the volume rendering (Figure 2a). To get an unobstructed view of the aortic arch however, a clipping plane is used to remove all voxels on one side of the plane from the rendering (Figure 2b). This plane was automatically reformatted and presented as an image slice next to the volume rendering (Figure 2c). The volume renderings present the data three-dimensionally in a visually feasible form, while the image contrasts in the reformatted slices

are typically better suited for quantitative measurements. Reformatted functional slices are seen in Figure 3 containing examples from a near-isotropic cine SSFP sequence (Figure 3a) and a three-component phase-contrast velocity acquisition (Figure 3b) obtained in a volunteer. The ability to define a region of interest and compute flow waveforms and absolute flow rates from an arbitrary 2D plane is demonstrated. For easy interpretation of direction and magnitude of velocities while interacting with the flow data, volume velocities were displayed in a color coded fashion comparable to color Doppler ultrasound. Only the through-plane velocity of the reformatted 2D slice is demonstrated, but displaying in-plane velocity components is possible as well.

Integration of morphology and function

Using planar reformatting of three-dimensional volumes, two-dimensional slices could be automatically aligned from different acquisitions obtained in the same scan session. In Figure 4 an example is provided, where a randomly chosen planar reformatting of a 3D cine SSFP acquisition is used to define an identical 2D slice in a three-component, 3D phase contrast blood velocity mapping acquisition. The signed flow vector magnitude of the in-plane up/down flow is shown in the figure, but as shown in Figure 3, e.g. through-plane flow could have been chosen instead. In Figure 5a volume rendered, isotropic, single-phase dataset is used as morphological placeholder for an anisotropic 2D phase contrast blood velocity mapping acquisition. In both figures, this allows proper localization of the morphology corresponding to the quantitative flow data.

Discussion

We have presented a new, integrated approach that standardizes morphological and functional image evaluation based on three-dimensional, isotropic MR image acquisitions. While this approach was recently evaluated for morphological imaging [15], the presented extension to functional data is

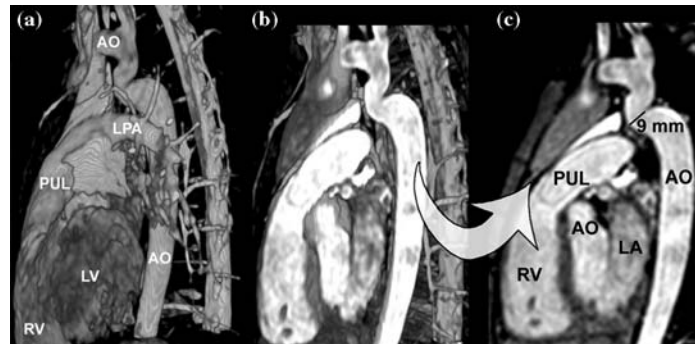


Figure 2. Integrated volume rendering and planar reformatting in a patient with kinking of the aorta. (a) Volume rendering of the entire dataset. (b) A plane was defined to cut the volume rendering. (c) Planar reformatting of the corresponding slice. Abbreviations: AO: aorta, LV: left ventricle, RV: right ventricle, PUL: pulmonary trunk, LPA: left pulmonary artery.

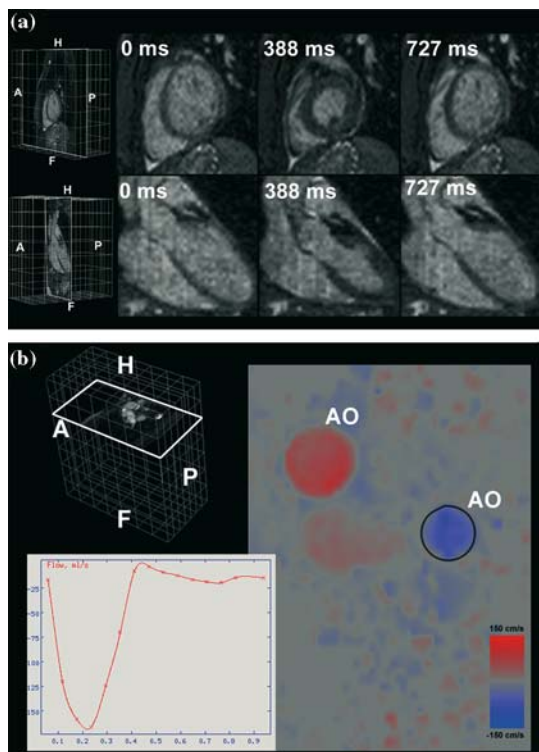


Figure 3. Isotropic cine- and three-dimensional flow imaging in a volunteer. (a) From a 2D multi-slice, multi-phase steady state free precession dataset, we have reformatted a short axis and a long axis view of the left ventricle. The corresponding time in the heart cycle is noted on each image. (b) The through-plane flow of an arbitrarily reformatted (in this case a transversal) slice is depicted. A region of interest was marked around the descending aorta (AO), and a flow curve plotted. The systolic flow peaks at 170 ml/s.

considered an important step towards fully operator-independent MRI examinations of congenital cardiac malformations. The obtained resolution however, a potentially important disadvantage of isotropic imaging, should be taken into consideration. Typically the in-plane resolution of a two-dimensional slice will exceed that of its three-dimensional counterpart. For a three-dimensional, isotropic scan we have to weigh the resolution demands against time consumption and signal-to-noise ratios. The important issue is to determine the minimal size of structures that should be identifiable and set the resolution accordingly. The concept of operator-independency was introduced by defining a small number of standardized protocols. To call these sequences truly operator-independent, any patient-specific adjustments necessary should be determinable objectively. As previously demonstrated, the setting of window acquisition lengths in morphological acquisitions can be defined by using a fast cine acquisition to determine the optimal diastolic time window when the heart is in the rest period [20]. For phase-contrast blood velocity mapping scans, some a priori knowledge about expected peak velocities is necessary in order to set velocity encoding correctly. Techniques have been described whereby acquisition of an extra segment allows automatic correction for aliased velocities to eliminate this restriction [25, 26]. With scan durations of the presented acquisitions of less than 30 min combined, they can all be acquired in a single scanning session. This can

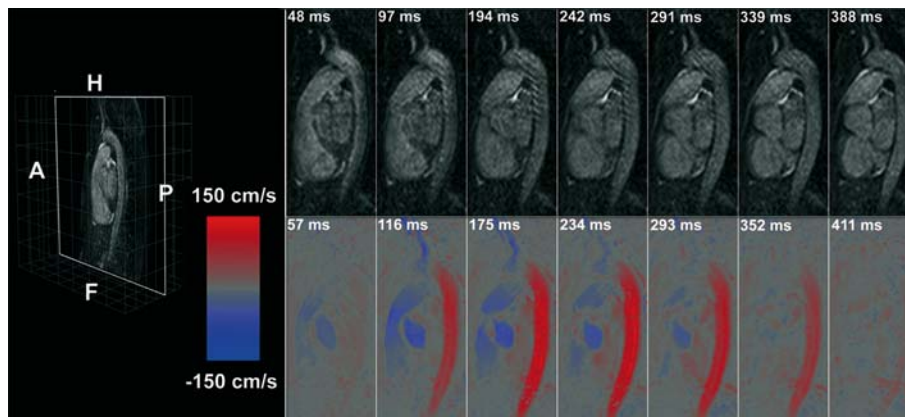


Figure 4. Aligning freely reformatted slices from a three-dimensional multi-phase steady state free precession acquisition and a three-component, three-dimensional flow acquisition. Both sequences were acquired with isotropic voxels for free reformatting in any imaging plane. The chosen reformatted plane is shown on the left. The time of acquisition in the heart cycle is shown on each image. The top row depicts the reformatted slices from the SSFP sequence, the bottom row the aligned reformatted in-plane flow along the up-down axis of the reformatted plane. Both sequences were acquired with phases throughout the entire heart cycle, but due to the size of the figure, only systolic phases are shown. The datasets were acquired from a volunteer.

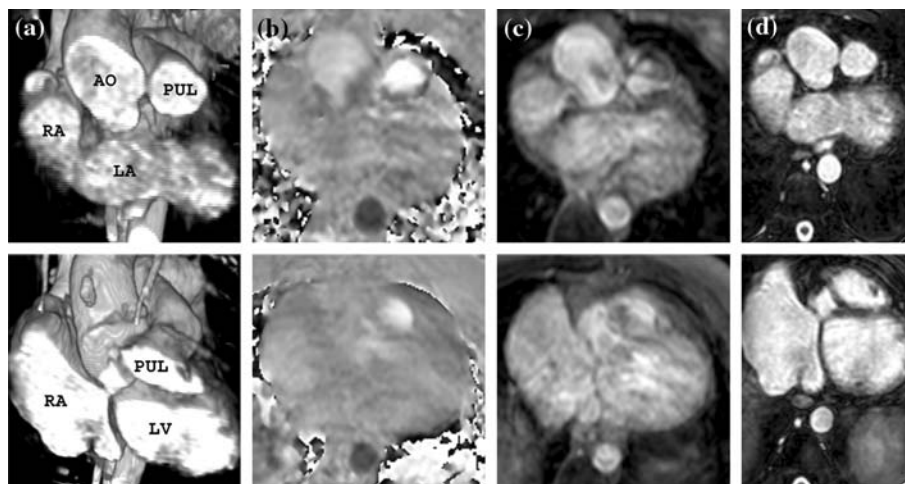


Figure 5. Using volume rendering of an isotropic, three-dimensional acquisition as a morphological placeholder of anisotropic two-dimensional scans. Each row corresponds to a unique plane. Columns 'b' and 'c' show the phase- and modulus images of a two-dimensional, single-slice flow acquisition. In column 'a' the position and angulation of the two-dimensional scan have been used to define clipping planes in the volume rendering, thus giving a morphological overview of each plane position. In column 'd' we reformatted the identical plane from the three-dimensional morphological acquisition. Abbreviations: AO: aorta, LA: left atrium, LV: left ventricle, RA: right atrium, PUL: pulmonary trunk.

be performed by a technician alone, without a radiologist or a cardiologist present to decide which acquisitions to make as is currently the situation for MR imaging in congenital heart disease. As a con-

sequence the expert is available for other tasks since diagnoses can be made at any time by any qualified radiologist or cardiologist using the post-processing tools discussed in this paper.

Interactive planar reformatting and two-dimensional quantification

Interactive reformatting and two-dimensional quantification tools allowed a truly free definition of 2D slices. It was easy to adjust the chosen plane in small, continuous steps with intuitive understanding of the direction of the change in relation to the anatomic structures. This made it easy to verify that the current slice was indeed the desired, simply by moving it slightly and compare to reference landmarks. These features hold potential for an improved reproduction of identical imaging planes in e.g. follow-up studies in individual patients or for comparison between different patients. Another benefit from this approach is that data can always be re-examined and corrected quantitative measurements made, if other imaging modalities or future examinations show contradictory results.

Integration of morphology and function

No datasets are optimal concerning all types of diagnoses. For example, from a morphological dataset a structural diagnosis can usually be obtained, but some difficulty delineating thin septal structures often remain. Hence, for the sizing of an atrial septal defect the value of a single-phase acquisition can be limited, while a flow sequence is more feasible. On the other hand, from an isolated flow acquisition it can be hard to determine with certainty that an obtained slice is indeed the desired. More credibility could potentially be put into a diagnosis if identical slices were available of both morphology and flow. In this case the morphological acquisitions could be used as a placeholder for the flow acquisition. The golden standard in imaging congenital heart disease is provided by echocardiography, a technique capable of imaging both morphology and function. Especially for the growing number of adults with complex congenital heart disease, MRI is increasingly used to supplement or even replace transthoracic echocardiography. The presented techniques to integrate cine and flow acquisitions could be seen analogous to the combination of traditional and Doppler echocardiography. With a

user interface to three-dimensional MRI imitating that of echocardiography [27], it would be easier to formally compare the two modalities in the future.

Limitations

Further clinical studies should be initiated to evaluate the concepts of isotropic functional cine and flow imaging that were introduced in this paper. Specifically, the in vivo accuracy of the individual components of the 3D phase contrast blood velocity measurements needs to be tested in pathological flows (e.g. septal defects, stenoses, and valvular regurgitations) before quantification of flow rates and velocity patterns can be trusted. We currently align sequences based on global position and angulation parameters as reported by the scanner. This approach raises some concern however. If one acquisition is acquired in breath holding and another during free breathing, the diaphragm (and hereby other structures) is often positioned differently between consecutive acquisitions, possibly invalidating the automatic alignment. This point should be addressed, e.g. as in [28]. Alternatively, the combined acquisition of cine and flow images in a single acquisition might alleviate this concern in the future [29].

Future perspectives

Several improvements that will greatly facilitate 3D MRI are just around the corner. A large reduction in scan times is to be expected for dynamic scans with the advent of $k-t$ blast and $k-t$ sense techniques [30]. This applies to both cine SSFP and phase-contrast velocity mapping scans [31, 32]. Implementation of slice following techniques [33] in 3D would make it possible to follow freely chosen anatomical structures during the cardiac cycle. For example, valve planes, septal defects, and outflow tracts could be tracked and visualized (cine and velocity reformatting) in one 2D plane throughout the cardiac cycle. The motion pattern could be quantified and the velocities and flow rates through these planes could be corrected for the cardiac motion itself. Additionally, other types of functional datasets obtained by MRI, such as perfusion data and tagging data for

quantification of myocardial motion, could be seamlessly integrated into the visualization tool to further increase the integration of morphology and function. Finally it seems obvious that in the future, the presented techniques should be made available directly on the scanner, to improve the acquisition planing of additional high-resolution scans when necessary.

Conclusions

This paper has suggested and discussed an integrated approach for interactive 2D and 3D offline “imaging” and quantification of operator independently acquired morphological and functional cardiac data with focus on congenital heart disease. The concept was proved by acquiring three-dimensional, isotropic acquisitions of morphology, cine and three component blood velocity data, and developing software for real time, interactive planar reformatting, visualization and quantification of integrated morphology, cine and flow data. The introduced ideas were demonstrated in selected clinical cases and in volunteers. Further studies are needed to evaluate the proposed scanning techniques under pathological condition, and clinical studies should finally be conducted to examine the benefit of the presented approach in the clinical setting.

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References

1. Song HK, Wright AC, Wolf RL, Wehrli FW. Multislice double inversion pulse sequence for efficient black-blood MRI. *Magn Reson Med* 2002; 47(3): 616–620.
2. Pereles FS, Kapoor V, Carr JC, et al. Usefulness of segmented true FISP cardiac pulse sequence in evaluation of congenital and acquired adult cardiac abnormalities. *AJR Am J Roentgenol* 2001; 177(5): 1155–1160.
3. Davlouros PA, Kilner PJ, Hornung TS, et al. Right ventricular function in adults with repaired tetralogy of Fallot assessed with cardiovascular magnetic resonance imaging: detrimental role of right ventricular outflow aneurysms or akinesia and adverse right-to-left ventricular interaction. *J Am Coll Cardiol* 2002; 40(11): 2044–2052.
4. Geva T, Greil GF, Marshall AC, Landzberg M, Powell AJ. Gadolinium-enhanced 3-dimensional magnetic resonance angiography of pulmonary blood supply in patients with complex pulmonary stenosis or atresia: comparison with X-ray angiography. *Circulation* 2002; 106: 473–478.
5. Barkhausen J, Ruehm G, Goyen M, Buck T, Laub G, Debatin JF. MR evaluation of ventricular function: true fast imaging with steady-state precession versus fast low-angle shot cine MR imaging: Feasibility study. *Radiology* 2001; 219(1): 264–269.
6. Alfakih K, Plein S, Bloomer T, Jones T, Ridgway J, Sivananthan M. Comparison of right ventricular volume measurements between axial and short axis orientation using steady state free precession. *J Magn Reson Imaging* 2003; 18: 25–32.
7. Bloomer TN, Plein S, Radjenovic A, et al. Cine MRI using steady state free precession in the radial long axis orientation is a fast accurate method for obtaining volumetric data of the left ventricle. *J Magn Reson Imaging* 2001; 14: 685–692.
8. Alfakih K, Plein S, Thiele H, Jones T, Ridgway JP, Sivananthan MU. Normal human left and right ventricular dimensions for MRI as assessed by turbo gradient echo and steady-state free precession imaging sequences. *J Magn Reson Imaging* 2003;17: 323–329.
9. Fieno DS, Jaffe WC, Simonetti OP, Judd RM, Finn P. TrueFISP: assessment of accuracy for measurement of left ventricular mass in an animal model. *J Magn Reson Imaging* 2002; 15: 526–531.
10. Powell AJ, Maier SE, Chung T, Geva T. Phase-velocity cine magnetic resonance imaging measurement of pulsatile blood flow in children and young adults: in vitro and in vivo validation. *Pediatr Cardiol* 2000; 21(2): 104–110.
11. Beerbaum P, Korperich H, Barth P, Esdorn H, Gieseke J, Meyer H. Noninvasive quantification of left-to-right shunt in pediatric patients: phase-contrast cine magnetic resonance imaging compared with invasive oximetry. *Circulation* 2001; 103: 2476–2482.
12. Kozerke S, Hasenkam JM, Pedersen EM, Boesiger P. Visualization of flow patterns distal to aortic valve prostheses in humans using a fast approach for cine 3D velocity mapping. *J Magn Reson Imaging* 2001; 13(5): 690–698.
13. Markl M, Chan FP, Alley MT, et al. Time-resolved three-dimensional phase-contrast MRI. *J Magn Reson Imaging* 2003; 17(4): 499–506.
14. Hjortdal VE, Emmertsen K, Stenbog E, et al. Effects of exercise and respiration on blood flow in total cavopulmo-

- nary connection: a real-time magnetic resonance flow study. *Circulation* 2003; 108(10): 1227–1231.
15. Sorensen TS, Körperich H, Greil GF, et al. Operator-independent isotropic 3D MRI for morphology in congenital heart disease – a validation study. *Circulation* 2004; 110(2): 163–169.
 16. Holmvang G, Palacios IF, Vlahakes GJ, et al. Imaging and sizing of atrial septal defects by magnetic resonance. *Circulation* 1995; 92(12): 3473–3480.
 17. Beerbaum P, Körperich H, Esdorn H, et al. Atrial septal defects in pediatric patients: noninvasive sizing with cardiovascular MR imaging. *Radiology* 2003; 228(2): 361–369.
 18. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. *Magn Reson Med* 1999; 42: 952–962.
 19. Fischer SE, Wickline SA, Lorenz CH. Novel real-time *R*-wave detection algorithm based on the vectorcardiogram for accurate gated magnetic resonance acquisitions. *Magn Reson Med* 1999; 42(2): 361–370.
 20. Plein S, Jones TR, Ridgway JP, Sivananthan MU. Three-dimensional coronary MR angiography performed with subject-specific cardiac acquisition windows and motion-adapted respiratory gating. *AJR Am J Roentgenol* 2003; 180(2): 505–512.
 21. Wang Y, Rossman PJ, Grimm RC, Riederer SJ, Ehman RL. Navigator-based real-time respiratory gating and triggering for reduction of respiration effects in three-dimensional coronary MR imaging. *Radiology* 1996; 198: 55–60.
 22. Botnar RM, Stuber M, Danias PG, Kissinger KV, Manning WJ. Improved coronary artery definition with T2-weighted, free-breathing, three-dimensional coronary MRA. *Circulation* 1999; 99: 3139–3148.
 23. Dønstrup S, Kozerke A, Kim WY, Boesiger P, Pedersen EM. 3D Measurement of velocity patterns in the left ventricle with navigator gating – in vitro evaluation and in vivo application. *Proc 7th Annual Meeting ISMRM*, 1999.
 24. Rezk-Salama C, Engel K, Bauer M, Greiner G, Ertl T. Interactive volume rendering on standard PC graphics hardware using multi-textures and multi-stage rasterization. *Proc ACM Siggraph/Eurograph Workshop on Graphics Hardware*, 2000.
 25. Swan JS, Grist TM, Weber DM, Sproat IA, Wojtowycz MM. MR angiography of the pelvis with variable velocity encoding and a phased-array coil. *Radiology* 1994; 190: 363–369.
 26. Ringgaard S, Oyre SA, Pedersen EM. Arterial MR imaging phase-contrast flow measurement: improvements with varying velocity sensitivity during cardiac cycle. *Radiology* 2004; July issue (In press).
 27. Teistker M, Bergmann J, Dormeier J, Dresing K, Franzen O, Habermann CR. The future viewing station: an intuitive and time-saving user interface beyond keyboard and mouse to improve CT and MRI based diagnosis. *RSNA Annual Meeting 2002; infoRAD 9501NT-i*.
 28. Spiegel MA, Luechinger R, Schwitler J, Boesiger P. Ring-Tag: ring-shaped tagging for myocardial centerline assessment. *Invest Radiol* 2003; 38(10): 669–678.
 29. Markl M, Alley MT, Pelc NJ. Balanced phase-contrast steady-state free precession (PC-SSFP): a novel technique for velocity encoding by gradient inversion. *Magn Reson Med* 2003; 49(5): 945–952.
 30. Tsao J, Boesiger P, Pruessmann KP. *k-t* BLAST and *k-t* SENSE: dynamic MRI with high frame rate exploiting spatiotemporal correlations. *Magn Reson Med* 2003; 50(5): 1031–1042.
 31. Kozerke S, Tsao J, Pruessmann KP, Boesiger P. Accelerating cardiac cine 3D SSFP imaging using *k-t* BLAST with integrated training. *Proc 11th Annual Meeting ISMRM*, 2003.
 32. Baltes C, Kozerke S, Tsao J, Pruessmann KP, Boesiger P. Eight-fold acceleration of PC-SSFP velocity mapping using *k-t* BLAST. *Proc 12th Annual Meeting ISMRM*, 2004; p. 1858.
 33. Kozerke S, Scheidegger MB, Pedersen EM, Boesiger P. Heart motion adapted cine phase contrast flow measurements through the aortic valve. *Magn Reson Med* 1999; 42: 970–978.
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