MR-GUIDED CARDIAC INTERVENTIONS USING MR-SAFE PASSIVE DEVICES: A PRECLINICAL STUDY AND FIRST-IN-MAN CONGENITAL INTERVENTIONS

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Short title: MR-Guided Congenital Cardiac Interventions

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Category: Advances in interventional cardiology

Word count:

a. Abstract: 250

b. Word length (including title page, abstract, text, references, tables, and figure legends): 5997

References: 40

Figures: 5

Journal Subject Codes: 23, 30, 41, 124

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ABSTRACT

Background: Percutaneous cardiac interventions are currently performed under X-ray guidance. Magnetic resonance imaging has been employed to guide intravascular interventions in the past, but mainly in animals. Translation of MR-guided interventions into humans has been limited by the lack of fully MR-compatible and safe devices, such as MR guidewires with mechanical characteristics similar to standard guidewires. The aim of the present study was to evaluate the safety and efficacy of a newly developed MR-safe and compatible passive guidewire in aiding MR-guided cardiac interventions in a swine model and describe the two first-in-man solely MR-guided interventions.

Methods and Results: In the preclinical trial, the new MR compatible wire aided the performance of 20 interventions in 5 swine. These consisted of balloon dilation of non-diseased pulmonary and aortic valves, aortic arch and branch pulmonary arteries. Catheter manipulations were monitored with real time MRI sequence with interactive modification of imaging plane and slice position. Following ethics and regulatory authority approval the two first-in-man MR-guided interventions were performed in a child and an adult, both with elements of valvar pulmonary stenosis. Both patients had successful relief of the valvar stenosis and were discharged home a few hours later with no complications.

Conclusions: The described pre-clinical study and case reports are encouraging that with the availability of the new MR compatible and safe guidewire, certain percutaneous cardiac interventions will become feasible to perform solely under MR-guidance. The benefits are clear with elimination of the use of ionising radiation and improvement of visualisation of the target lesions.

Key words: Magnetic resonance imaging, catheterization, angioplasty, heart defects, congenital
INTRODUCTION

Diagnosis and treatment of patients with congenital heart disease has improved considerably over the past few decades, with more patients surviving into adulthood and more complex operations and interventions being performed across all age groups. Whilst cardiac anatomy and function can be easily assessed by echocardiography or MRI, hemodynamic pressure measurements can only be performed invasively, mainly under X-ray guidance. However, the use of radiation during repetitive X-ray guided catheterization has led to concerns relating to the risk of solid tumours in later life, and that is particularly true in children in whom increased radiosensitivity, coupled with the possibility of repetitive exposure to diagnostic and interventional X-Ray procedures, can lead to a significant increase of cancer risk.

In contrast, MR-guided diagnostic cardiac catheterizations involve no exposure to radiation and are currently established in some centers as their preferred method for assessment of pulmonary vascular resistance in children and adults. As well as providing hemodynamic data, MRI-guided catheterization procedures provide useful additional information, such as detailed delineation of the cardiac anatomy, flows across valves and in large vessels, pressure-volume loop relationships and ventricular function, leading to more accurate and informed treatment stratification and assessment of outcome. Furthermore, real-time visualisation of the cardiovascular structures in any required spatial orientation, and more detailed additional information obtained from 3D MRI scans, can be of particular benefit in patients with complex congenital heart disease.

Although, MR-guided diagnostic catheterizations are feasible without the use of a guidewire, catheter interventions nearly always require a suitable guidewire to aid and support the procedures. Standard guidewires, approved for x-ray procedures, are manufactured from Nickel-Titanium superelastic memory alloys (Nitinol) or stainless steel. Due to the conductive properties of these materials and the length of the guidewire, radiofrequency (RF) coupling can cause significant heating of the material, hence metallic guidewires are not applicable for MR-guided interventions in patients.
Continuous development of software and hardware has allowed the application of interventional MRI (i-MRI) in animal models for many procedures currently performed under X-ray guidance and for the in vivo monitoring of catheter-based vascular gene delivery.\textsuperscript{9-13} However, some of the guidewires used in these studies, have not been proven to be RF safe,\textsuperscript{13} whereas other RF safe polymer guidewires have not been found to conform mechanically to norms and do not provide adequate support for the interventional procedures.\textsuperscript{12, 14} Overall, there have been no interventions in an animal model to date using a guidewire that is fully MR compatible and RF safe and has mechanical properties similar to the standard nitinol or stainless steel guidewires used in the X-Ray cardiac catheterization laboratory. As a result, none of the above promising approaches for MRI-guided interventions had been translated so far into the clinical setting. An MR-safe guidewire with the mechanical features of a standard nitinol guidewire was developed and proposed recently.\textsuperscript{15} This is the first guidewire that fulfils all prerequisites to become a clinical device with both actual safety proof and norm-conforming mechanical properties.

In the present study we report a. the in vitro assessment of the guidewire’s behaviour when guiding and supporting MR-compatible catheters and valvuloplasty balloons for MR-guided interventions and b. the first-in-man MR-guided congenital cardiac interventions for two patients with pulmonary valve stenosis.

**METHODS**

**Instruments**

*a. guide wire*

A non-metallic MR-compatible and safe guide wire (MR-GW) with features, properties and safety characteristics as described previously was used for all interventions.\textsuperscript{15} The core of the MR-GW consists of an MR-safe glass fibre-compound and is produced using micro-pultrusion leading to a compound fibre with excellent flexural and torsional stiffness and improved kinking properties as compared to PEEK-based MR guide wires proposed previously.\textsuperscript{14} A 10cm long cone-shaped Nitinol tip section is attached distally to provide
superelasticity, higher flexibility and to allow shaping of the tip. The compound material is doped with iron at a concentration of 1% of the effective matrix mass to provide MR visibility over the full length. For accurate localization of the tip, additional tiny iron splints of 50µm diameter and 2mm length are affixed along the distal 10 cm of the MR-GW every 2cm, and then every 5cm for the next 30cm. A biocompatible hydrophilic coating (Lubriteq, Hemoteq AG, Würselen, Germany) covers the jacket to reduce blood clotting and to ensure proper gliding within catheters and vessels. The diameter of the MR-GW is 0.032” and comes in different lengths of 200 -300 cm.

b. catheters

A balloon wedge pressure catheter (Arrow, Reading, PA, USA) was used for right and left heart catheterization and to approach the target lesion. The balloon of the wedge catheter was filled with CO₂ and was passively visualised as a dark circular signal void in the bright blood pool on the SSFP images.¹⁶ Commercially available, MR compatible valvuloplasty catheters (Tyshak II, NuMED, Hopkington, NY) were used for balloon dilation of the great arterial valves, aortic arch and branch pulmonary arteries.

The authors had full access to the data and take responsibility for its integrity. All authors have read and agree to the manuscript as written.

Animal study

Five female domestic pigs were included in the current study, as approved by the government committee on animal experiments. All interventions were carried out under general anesthesia. The new MR-GW was used to aid balloon dilation of non-diseased pulmonary and aortic valves, aortic arch and branch pulmonary arteries. Each procedure was carried out twice in each animal and performed by two different operators out of a group of three experienced interventionalists (GK, AT and RR). Invasive pressure monitoring was not performed as there were no stenotic lesions and the main interest of the study was to assess the behaviour of the guidewire.
All interventions were performed on a clinical 1.5 T interventional MR system (Achieva, Philips, Best, Netherlands). The images were displayed at the console and mini-console next to the magnet. Interactive real-time MR scanning was used to monitor the motion of the devices. Changes of the imaging planes and slice position were interactively performed to ensure constant visualization of the interventional devices.

For right heart catheterization the balloon wedge pressure catheter was inserted in the right femoral vein and advanced into the inferior vena cava. For passive catheter tracking the tip of the balloon was inflated with 1.25 ml of CO₂ and advanced into the right atrium. The balloon of the wedge pressure catheter was clearly visible as a dark signal void within the surrounding bright blood (Figure 1). When the catheter reached the right ventricular outflow tract, the guidewire was introduced into it to increase torque and stability. The pulmonary valve was crossed with the catheter-wire ensemble, which was advanced into one of the branch pulmonary arteries and the catheter was withdrawn. The different spacing of the iron-splints on the wire allowed visual assessment of the wire length into the branch pulmonary artery (Figure 1). For example, the operator knew that the distal 10 cm of the wire were already advanced into the pulmonary artery, when the distance of the iron splints, visible as small signal voids increased to 5 cm. The balloon valvuloplasty catheter was introduced over the wire and placed across the pulmonary artery. In order to increase visibility of the valvuloplasty catheter and facilitate correct positioning 1 ml of Gd-DTPA (Magnevist, Beyer-Schering, Berlin, Germany) diluted in saline (1:10) was injected into the balloon. After the balloon was placed across the pulmonary valve it was manually inflated with diluted Gd-DTPA up to 2 Atm and the pressure maintained for 5 seconds. With the wire in a stable position wedged into one of the pulmonary arteries, the valvuloplasty catheter was advanced into a branch pulmonary artery and balloon dilation was performed.

For left heart catheterization the balloon wedge pressure catheter was advanced into the descending aorta, being clearly visible as a dark signal void (Figure 2). The tip of the guidewire was shaped to a hook configuration and the guide wire advanced via the catheter into the aortic arch. Subsequently, the catheter and the guidewire were advanced into the
ascending aorta and the aortic valve was crossed. The balloon valvuloplasty catheter was manually inflated with diluted Gd-DTPA up to 2 Atm at a sustained pressure for 5 seconds. With the wire in a stable position in the left ventricle, the valvuloplasty balloon was withdrawn to a level distal to the left subclavian artery and balloon dilation of the aortic arch was performed (Figure 2).

First in man congenital cardiac interventions

Ethical approval was obtained by an expert device research ethics committee for the performance of MRI-guided interventions for adults and children > 2 years of age with congenital heart disease. The new MR-GW was assessed and approved by the United Kingdom Medicines and Healthcare Products Regulatory Agency (MHRA).

Two patients with pulmonary valve stenosis underwent MR-guided balloon dilation of their pulmonary valves. The first patient was 6 years old and had progression of valvar pulmonary stenosis (PS) over the years to moderately-severe level with echocardiographic peak gradient of 63 mmHg. Following informed consent the parents opted for the MR-guided interventional study. The second patient was a 43-year old man with valvar and subvalvar pulmonary stenosis and severe right ventricular hypertrophy. Doppler Echocardiography revealed double envelope, indicating both valvar and subvalvar pulmonary stenosis and a peak gradient of 110mmHg. Both patients had an intact septum, were fully saturated and were clinically asymptomatic.

The procedures were performed on an interventional 1.5T MR-scanner (Achieva, Philips, Best, Netherlands) in our combined X-Ray/MRI laboratory with the X-Ray equipment readily available for emergency bailout if required. We used the commercially available hemodynamic monitoring system EP Tracer 102 (CardioTek B.V, Maastricht, Holland) for hemodynamic pressure monitoring. The hemodynamic traces were displayed on one of the 2 panels in the mini in-room console, with the other panel displaying the i-MRI sequences. The operator could start and stop the interactive scanning independently using foot pedals, which also facilitated the adjustment of the imaging plane and slice position in order to get the
interventional devices in view. The latter was achieved with the foot pedal function, which rotates through four pre-selected imaging planes and the pedal pull/push action.

Cannulation of the femoral vessels was performed at the beginning of the procedure and the patient was moved into the MRI scanner. For both patients the same scan protocol with similar scan parameters were used (Table 1), except for a higher spatial resolution used in the pediatric case. Following a plan-scan and sense reference scan, 2D SSFP cine MRI was performed in the RVOT and axial short axis across the pulmonary valve allowing initial assessment of the valve lesion. An ECG-triggered, free-breathing 3D SSFP scan and 2D quantitative phase contrast flow scans (Table 1) were used to measure the lesion size and maximum flow velocity through the lesion.

The common imaging planes for catheter guidance were identified and stored for use during interactive real-time balanced steady state free precession (SSFP) sequence using cartesian acquisition of k-space lines. Balloon visualisation was facilitated with injection into the balloon lumen of Endorem 5% (for the adult patient) and dilute Gadolinium 1:10 (for the pediatric patient). Cine and phase contrast flow images were repeated after the intervention, to assess the hemodynamic result and the patients were extubated in the MRI suite and transferred to the ward.

RESULTS

Clinical case 1 (Pediatric). Cine MRI assessment of the pulmonary valve revealed bicuspid pulmonary valve (BPV) with diameter of 22x22mm and effective orifice area of 49mm². A 6Fr wedge catheter was used for right heart catheterization and to cross the pulmonary valve. Baseline hemodynamic gradient between the right ventricle (RV) and the main pulmonary artery (MPA) was 44mmHg. The wedge catheter was advanced to the distal LPA and the MR wire was introduced through the catheter to the distal vasculature and visualised on the sagittal view with the iron splints easily visible. We observed no artifacts caused by the iron markers on the wire. A 22mm Tyshak balloon was initially used and inflated for 5sec. The waste seen on it was completely abolished (Figure 3). Repeat pressure measurement
revealed mild gradient improvement to 30mmHg, hence a 25mm Tyshak II balloon was inflated across the valve as previously. Repeat gradient assessment showed further improvement to 25mmHg. No further attempts on inflating the pulmonary valve with a bigger balloon were made, due to the bicuspid nature of the valve and the fact that balloons bigger that 25mm would be inappropriately big for a child of this age. Total catheterisation procedure time was 90min. Occasional ventricular ectopic beats were noted during the catheterisation but the patient did not suffer any sustained arrhythmias. Repeat cine MRI assessment revealed increase of the effective orifice area on of the pulmonary valve from 49 to 92mm². Phase contrast flow images showed no valvar regurgitation before and mild valvar regurgitation after the procedure (regurgitant fraction of 7%). Peak echocardiographic gradient improved from 63mmHg prior to the procedure to 22mmHg after the procedure and the patient was discharged home a few hours later uneventfully.

**Clinical case 2 (Adult).** The patient had known valvar and subvalvar pulmonary stenosis, hence it was decided to alleviate the valvar component and reassess the subvalvar gradient at later stage. Cine MRI assessment of the pulmonary valve revealed valve diameter of 21x24mm. In-plane phase contrast flow images showed maximum velocity across the pulmonary valve and the sub-valvar lesion of 3.1m/s and 2.3m/s, respectively. A 6Fr wedge catheter was used for right heart catheterization and to cross the pulmonary valve. The wedge catheter was advanced into the LPA and then in the LPA wedge position. The MR compatible guidewire was advanced into the LPA distally and the wire position was confirmed on the LPA saggital view, where the iron markers of the wire were easily visible. The wedge catheter was withdrawn and a 23mm Tyshak II balloon was advanced over it. Visualisation of the balloon was achieved with injection of 1ml of 5% Endorem contrast inside the balloon. After correct positioning was confirmed, a full inflation was performed on the saggital RVOT view (Figure 4). Repeat pressure measurement did not reveal significant hemodynamic improvement, hence a 25mm Tyshak balloon was chosen and inflated across the pulmonary valve. RV pressure at the end of the procedure remained systemic due to infundibular collapse, as evidenced on the hemodynamic trace and the phase contrast flow
images (Figure 5). The latter showed change of the forward flow jet direction from eccentric, directed towards the superior wall of the main pulmonary artery, to a central one, but with associated subpulmonary infundibular collapse. Velocity across the valve and sub-valvar lesion was 2.5m/s and 2.6m/s, respectively. Gradual pullback from the MPA to beneath the pulmonary valve and then to the RV revealed a gradient of 17mmHg across the pulmonary valve and 60mmHg across the infundibular stenosis, confirming our initial suspicions that a significant subvalvar component was going to be present at the end of the procedure. Total catheterisation procedure time was 110min. The patient did not suffer any complications. Peak echocardiographic gradient prior to the procedure was 110mmHg with double envelope trace (indicating valvar and subvalvar stenosis), which improved to 70mmHg after the procedure with change of the Doppler pattern from double to single envelope. The patient was commenced on b-blockade with propranolol, in an attempt to induce infundibular relaxation, until such time that the RV hypertrophy regressed sufficiently as a response to the valvar stenosis relief. No complications were noted and the patient was discharged home the following day. Repeat echocardiography 2 months after the procedure revealed further RVOT gradient reduction to 45mmHg.

DISCUSSION

Since 2001 there have been a number of animal studies showing the safety and efficacy of i-MRI for a multitude of procedures that are currently performed under x-ray guidance. In particular, animal i-MRI has been used to facilitate procedures such as creation or closure of atrial septal communications, intracoronary imaging as well as balloon angioplasty and stent implantation in coronary and carotid arteries, stenting of pulmonary arteries, stenting of aortic coarctation and vena cava interventions. The procedures have been aided by the use of non MR-safe active guidewires and prototype or commercially available devices and were either solely MR-guided or combined with conventional catheterization before and after the procedure.
Active guidewires are tracked or visualized by employing miniature RF-coils or loopless antenna both connected to the scanner using a long metallic wire. This long wire can heat up during certain MRI sequences due to resonating RF waves. Despite modifications to reduce the risk of heating with active devices, under certain conditions heating at the tip can occur up to 70°C with obvious associated risks. New strategies for safe active devices have been proposed including optical transmission and use of transformers to shorten the length of the conducting wire,\textsuperscript{32,33} however no safe active guidewires have been developed so far. Semi-active catheters use tuned fiducial markers that produce increase MR signal locally without wires connecting to the scanner.\textsuperscript{34} There are however issues with miniaturisation and the ability of firmly securing these markers to catheters. Passive guide wires have the advantage of no risk of heating and lower cost, but the disadvantage of being less visible than active guide wires and requiring manual tracking and changing of the imaging plane to keep the wire in view.

Left heart MRI guided cardiac interventions have also been performed without the use of a guidewire in the LV, in an animal model for transcatheter implantation of a prosthetic valve in the aortic valve position,\textsuperscript{35} where the use of susceptibility markers enabled precise position monitoring of the interventional instrument and in patients who underwent balloon dilation of aortic coarctation.\textsuperscript{36} In the last study, the procedures were preceded and followed by conventional catheterization to assess the arch angiographically and measure pressure gradients across the coarctation segment and a non MR-safe guidewire was used. The wire was withdrawn before the patient entered the MR scanner and another self-made non-metallic guidewire was advanced just up to the distal port of the balloon catheter and the procedure was completed under MR guidance.

Translation of the animal MR-guided interventions in humans had not been made possible to date due to the lack of fully MRI compatible equipment. Recently an MR-safe guidewire fulfilling all prerequisites to become a clinical device with the mechanical features of a standard nitinol guidewire has been developed. As a pre-clinical step, we used this guidewire in combination with already available MRI safe catheters to perform solely MR guided
cardiac interventions in an animal model successfully. Following ethical and device regulatory approval we used the guidewire to perform the two first-in-man congenital interventions. The interactive scanning parameters were optimised to improve temporal resolution (Table 1). Although, still much lower than conventional X-Ray imaging, the temporal resolution achieved was perfectly acceptable to the operators, whose work was also greatly assisted by having the option of changing the imaging planes and slices independently.

Our first patient had a bicuspid pulmonary valve, a very rare congenital entity encountered in only 0.05-0.1% of the population. Although, complete abolition of the balloon waist was achieved, there was still some residual pulmonary stenosis gradient at the end of the procedure, which was attributed to the bicuspid nature of the valve. The patient’s hemodynamic gradient was reduced by 43% and his peak echocardiographic gradient by > 60%. Our second patient was complicated by dual pathology with valvar and subvalvar pulmonary stenosis. Hemodynamic and MRI assessment at the end of the MR-catheterisation procedure revealed that the valvar gradient was now negligible. Echocardiographically, the RVOT gradient decreased by 60%.

Total catheterisation time in both patients was longer than the matched interventions performed in the catheterisation laboratory, but we interpreted this as having to do with our learning curve. This was not at the expense of the patients as no ionising radiation was involved. The contrast material used to facilitate better visualisation of the valvuloplasty balloon differed between the pediatric and the adult case. This was due to the fact that the iron oxide agent Endorem, which would have been our preferred choice across all ages due to its superior visualisation properties, is not currently licenced for children.

We have been encouraged by the successful outcome of our first two clinical cases, but we need to evaluate the feasibility, safety and efficacy of the MR-guided interventions further. To this end, a clinical trial on MR-guided cardiac interventions for commonly encountered lesions, such as aortic and pulmonary valve stenosis, branch pulmonary artery or aortic arch stenosis or dilatation of stents previously implanted in those vessels is ongoing. A committee
has been set up to assess the safety and clinical outcome of the interventions. We hope that in the future MR-guided interventions will start replacing some cardiac catheterisation procedures performed in patients with congenital heart disease. The option of performing such interventions in the MRI suite is particularly appealing for its obvious benefits of lack of radiation, additional physiological assessment and soft tissue characterisation. The latter is of particular relevance in interventional procedures, as real time i-MRI would offer early recognition and response to complications such as vascular rupture or impeding cardiac tamponade.

CONCLUSION

We have demonstrated the feasibility of performing balloon valvuloplasty procedures using a new MR safe and compatible guidewire in an animal model and applied it in the two first in-man clinical cases. MRI-guided cardiac interventions, particularly in congenital heart disease may have a significant role to play in patients who require simple interventions in order to decrease or eliminate their radiation exposure, whilst improving lesion visualisation and interventional precision.

ACKNOWLEDGMENTS AND FUNDING SOURCES

The authors acknowledge financial support from the “Stiftung Industrieforschung”, grant-ID:S737 and Bundesministerium für Wirtschaft und Technologie, InnoNET 16IN0461, Germany and the UK Department of Health via the National Institute for Health Research (NIHR) comprehensive Biomedical Research Centre award to Guy's & St Thomas’ NHS Foundation Trust in partnership with King's College London (AT).

We are also very grateful to Paul James, Aaron Bell, Philipp Beerbaum, Jouke Smink and the radiographers and technicians for their help with the clinical cases.

DISCLOSURES

The investigators received research grant support from Philips Healthcare.
References


FIGURE LEGENDS

Figure 1: Dilatation of the pulmonary valve in the swine. The images show the CO₂ filled wedge catheter as a dark spot in the inferior vena cava (1), the right atrium (2), the right ventricle (3) and the main pulmonary artery (4,5). The guidewire was inserted into the catheter and advanced into the right pulmonary artery (6). The balloon wedge catheter was exchanged for the valvuloplasty catheter and advanced to the pulmonary valve. The balloon was inflated with diluted Gd-DTPA (7 and 8 asterisk) and the pulmonary valve was dilated.

Figure 2: The CO₂ filled wedge catheter is seen in the descending aorta (1), with the wire advanced into the ascending aorta (2, open arrows: guidewire) and into the left ventricle. The valvuloplasty catheter is inflated across the aortic valve (3) and distal to the left subclavian artery (4).

Figure 3: Dilatation of the pulmonary valve in a pediatric patient. The valvuloplasty balloon (asterisk) was inflated with diluted Gd-DTPA and the pulmonary valve was dilated.

Figure 4: Dilatation of the pulmonary valve in an adult patient. The CO₂ filled wedge catheter appears as a dark spot in the right ventricle, (1) main pulmonary artery (2) and the left pulmonary artery on the saggital view. The course of the guidewire with its iron markers is seen on the saggital view of the IVC/RA junction (4) and from the RV into the left pulmonary artery (5). The valvuloplasty balloon was inflated with 5% Endorem (6 asterisk) and the pulmonary valve was dilated.

Figure 5: Phase contrast flow images showing change of the forward flow jet direction from eccentric, directed towards the superior wall of the main pulmonary artery before the procedure (A), to central with associated subpulmonary infundibular collapse (B).
Table 1: MR-scan parameter of the patient scans for the assessment of function, anatomy, angiography, flow and intervention

<table>
<thead>
<tr>
<th>Scan Type</th>
<th>Patient 1 (6 years)</th>
<th>Patient 2 (42 years)</th>
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<tbody>
<tr>
<td>Function - 2D/M2D Cine</td>
<td>Res.: 1.7x1.7x8 mm³ SENSE = 2 SSFP-contrast TR/TE = 3.2/1.6ms Flip-angle = 60 Heart phases 60 Breathhold 14s</td>
<td>Res.: 2.2x2.2x10 mm³ SENSE = 2 SSFP-contrast TR/TE = 3.0/1.5ms Flip-angle = 60 Heart phases 40 Breathhold 15s</td>
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<tr>
<td>Anatomy – 3D whole heart</td>
<td>Res.: 1.3x1.3x1.3 mm³ SENSE = 2 SSFP-contrast TR/TE = 4.9/2.4ms Flip-angle = 90 T2-prep TE=35ms TFE-factor=20 ECG trigger: diastole Free-breathing, resp. gating window= 3mm Scan time 3min (100% efficiency)</td>
<td>Res.: 1.6x1.6x1.6 mm³ SENSE = 2 SSFP-contrast TR/TE = 4.7/2.3ms Flip-angle = 90 T2-prep TE=35ms TFE-factor=28 ECG trigger: diastole Free-breathing, resp. gating window= 3mm Scan time 3.4min (100% efficiency)</td>
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<tr>
<td>Angiography – 3D MRA</td>
<td>Res.: 1.8x1.8x1.8 mm³ SENSE = 2 T1-contrast TR/TE = 4.1/1.3ms Flip-angle = 40 Single breathhold</td>
<td>Res.: 2.2x2.2x2.2 mm³ SENSE = 2 T1-contrast TR/TE = 3.5/1.1ms Flip-angle = 40 Single breathhold</td>
</tr>
<tr>
<td>Flows – In/through-plane 2D-PCA</td>
<td>Res.: 1.6x1.6x6 mm³ SENSE = 2 T1-contrast TR/TE = 4.7/2.9 Flip-angle = 15 VENC=350cm/s</td>
<td>Res.: 2.2x2.7x6mm³ SENSE = 2 T1-contrast TR/TE = 4.3/2.6 Flip-angle = 15 VENC=380cm/s</td>
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<tr>
<td>Intervention - real-time interactive</td>
<td>Res.: 2.2x2.2x8 mm³ SENSE = 1.5 SSFP-contrast TR/TE = 2.5/1.1ms Partial Echo Half-scan=0.62 Flip-angle = 45 Temp. Res: 11 images/s</td>
<td>a)Res.: 2.5x2.5x10 mm³ SENSE = 1.5 SSFP-contrast TR/TE = 2.4/1.0ms Partial Echo Half-scan=0.62 Flip-angle = 45 Temp. Res: 12 images/s</td>
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<td></td>
<td></td>
<td>b)Res.: 4x5x8 mm³ SSFP-contrast TR/TE = 2.6/1.3ms Flip-angle = 45 Temp. Res: 7 images /s</td>
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