European Journal of Radiology 81 (2012) e929–e937

Contents lists available at SciVerse ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

4D phase contrast flow imaging for in-stent flow visualization and assessment of stent patency in peripheral vascular stents – A phantom study

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ARTICLE INFO

Article history:
Received 19 December 2011
Received in revised form 26 April 2012
Accepted 4 May 2012

Keywords:
4D flow imaging
2D flow imaging
Phase contrast MRI
Contrast enhanced MRA
Vascular stents

ABSTRACT

Purpose: 4D phase contrast flow imaging is increasingly used to study the hemodynamics in various vascular territories and pathologies. The aim of this study was to assess the feasibility and validity of MRI based 4D phase contrast flow imaging for the evaluation of in-stent blood flow in 17 commonly used peripheral stents.

Materials and methods: 17 different peripheral stents were implanted into a MR compatible flow phantom. In-stent visibility, maximal velocity and flow visualization were assessed and estimates of in-stent patency obtained from 4D phase contrast flow data sets were compared to a conventional 3D contrast-enhanced magnetic resonance angiography (CE-MRA) as well as 2D PC flow measurements.

Results: In all but 3 of the tested stents time-resolved 3D particle traces could be visualized inside the stent lumen. Quality of 4D flow visualization and CE-MRA images depended on stent type and stent orientation relative to the magnetic field. Compared to the visible lumen area determined by 3D CE-MRA, estimates of lumen patency derived from 4D flow measurements were significantly higher and less dependent on stent type. A higher number of stents could be assessed for in-stent patency by 4D phase contrast flow imaging ($n = 14$) than by 2D phase contrast flow imaging ($n = 10$).

Conclusions: 4D phase contrast flow imaging in peripheral vascular stents is feasible and appears advantageous over conventional 3D contrast-enhanced MR angiography and 2D phase contrast flow imaging. It allows for in-stent flow visualization and flow quantification with varying quality depending on stent type.

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1. Introduction

Over the last years, 4D phase contrast (PC) flow imaging has emerged as a powerful technique for the characterization of flow phenomena associated with vascular pathologies. Several studies have demonstrated its ability to visualize blood flow patterns in various vascular territories [1–3]. By providing a better insight into blood hemodynamics, 4D phase contrast flow imaging has the potential to contribute to a better understanding of the mechanisms involved in stenosis formation, thrombembolism from atherosclerotic plaque as well as vascular aneurysm growth and rupture [2,4,5]. In contrast to 2D PC flow imaging, which requires precise planning during the examination, the volumetric data of a 4D PC scan allows for offline planning of measurement planes, which may be particularly useful for blood flow quantification in complex vascular geometries [3].

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http://dx.doi.org/10.1016/j.ejrad.2012.05.032

In addition to visualizing blood flow patterns associated with vascular pathologies, 4D flow imaging may help to monitor and understand the alterations in hemodynamics induced by endovascular implants such as vascular stents and valve protheses [6,7].

Stent imaging and assessment of stent lumen patency using magnetic resonance imaging is significantly complicated by stent associated artifacts [8,9]. The severity of such artifacts depends on stent characteristics such as stent material and design as well as imaging parameters [10,11]. However, new stent designs and materials have significantly improved the evaluation of in-stent lumen patency by MR techniques. The feasibility of stent evaluation using MR techniques has been demonstrated for contrast enhanced angiography sequences as well as for 2D phase contrast flow imaging by a number of studies [8,10,12–14].

To our knowledge so far no systematic evaluation of the feasibility of 4D phase contrast flow imaging for peripheral vascular stents exists.

In our present study we aimed at assessing the quality of time-resolved 3D particle trace visualization as well as the validity of in-stent 4D flow measurements inside the lumen of various peripheral vascular stents.

In addition, we compared estimates of in-stent lumen patency derived from 4D flow measurements to values obtained from conventional 2D phase contrast flow measurements and 3D contrast-enhanced MR angiography images.

2. Materials and methods

2.1. Stents

We analyzed 17 stent types made of different materials and design. The stent materials comprised 5 steel (316L), 1 cobalt superalloy, 9 nitinol and 2 tantalum stents. Nominal stent diameters were 5, 7 and 8 mm as indicated by manufacturers. For details see Table 1.

2.2. Flow phantom

All stents were inserted into plastic tubes with inner diameters equivalent to the nominal diameter of the corresponding stent. The plastic tubes were placed in boxes filled with a solid gel (Dubliplast, Dentaurum AG, Pforzheim, Germany), which gave a homogenous stationary background signal. The plastic tubes were individually connected to a high precision flow pump (MCP Z PROCESS, Ismatec SA, Glattbrugg, Switzerland) positioned outside the scanner room. The flow pump produced a continous flow; delivery speed was set to maximum. In order to simulate blood viscosity an isotone saline solution admixed with glycerine (ratio of 100:40) was used as previously described [15]. At room temperature dynamic viscosity of this solution is equal to 3.72 mPa s. 10 ml SabSimplex/l (Pfizer Pharma GmbH) were added to suppress foaming. Furthermore 2 ml/l Gadobutrol (Gadovist 1 mmol/ml, Bayer) was added in a dosage close to what would be used in an in vivo situation [8]. Flow velocities were calculated from direct measurement of liquid throughput for the corresponding tube diameters based on the following formula (1):

$$\text{average flow velocity}\,[\text{cm/s}] = \frac{\text{volume per time}\,[\text{cm}^3/\text{s}]}{\text{lumen area}\,[\text{cm}^2]} \quad (1)$$

Maximal flow velocities were calculated based on the fact that maximal velocities are double the average velocity under laminar flow conditions [16], which are consistent with a parabolic velocity distribution for newtons fluids. Resulting estimates for maximal flow velocities were as follows: 44.15 cm/s for 5 mm tubes, 33.55 cm/s for 7 mm tubes and 31.96 cm/s for 8 mm tubes. Respective Reynolds numbers were 326.2 for 5 mm tubes, 346.9 for 7 mm tubes and 377.7 for 8 mm tubes, all constistent with laminar flow.

2.3. MRI exams

All MR exams were performed on a clinical 1.5 T scanner (Achieva 2.6, Philips, Best, The Netherlands). For signal detection a 14 channel receive-only surface coil was used (Philips, Hamburg).

The flow phantoms were positioned into the isocenter of the scanner. All measurements were performed with the stents orientated parallel and then perpendicular to the main magnetic field (B_0). Phase encoding direction was anterior–posterior for all measurements. Frequency encoding was parallel to the stent orientation, i.e. feet-head with the stent parallel to B_0 and right-left with the stent orthogonal to B_0.

A retrospectively triggered 4D PC flow sequence with velocity encoding in all 3 directions was used. For comparison a conventional 3D contrast enhanced MR angiography sequence (3D CE-MRA) and a 2D phase contrast (PC) flow sequence with through-plane velocity encoding were acquired. See Table 2 for details of sequence parameters.

Velocity encoding of the PC flow sequences were adjusted to maximal flow velocities (60 cm/s) to avoid alaising. The MR scanner generated an internal trigger signal simulating a heart rate of 60 bpm.

Table 1
Stent characteristics.

No.	Name	Manufacturer	Material	Length [mm]	Diameter [mm]	Lumen area [mm^2]
1	SelfX Xpert	Abbott	Nitinol	20	5	19.6
2	Absolute	Abbott	Nitinol	60	7	38.5
3	AccuLink Carotid	Abbott	Nitinol	40	7	38.5
4	Express Vascular LD	Boston Scientific	316L	37	7	38.5
5	OmniLink 0.018	Abbott	316L	18	7	38.5
6	OmniLink 0.035	Abbott	316L	35	7	38.5
7	Palmaz Corinthian IQ	Cordis	316L	40	7	38.5
8	Renal109	Abbott	Tantalum	18	7	38.5
9	Renal137	Abbott	Tantalum	18	7	38.5
10	Sentinol	Boston Scientific	Nitinol	59	7	38.5
11	Symphony	Boston Scientific	Nitinol	40	7	38.5
12	Vascuflex SE	B. Braun	Nitinol	20	7	38.5
13	Wallstent Uni	Boston Scientific	Cobalt-Superalloy	60	7	38.5
14	Zilver	Cook	Nitinol	40	7	38.5
15	Evo	pfm	Nitinol	50	8	50.3
16	RxCarotid	Abbott	Nitinol	30	8	50.3
17	SAXX Large	Devon	316L	35	8	50.3

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