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Correlation between Hemodynamic Parameters and Intra-Arterial Septum Motion in DeBakey Type III Aortic Dissections Using 2D pcMRI and 4D MRA

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Abstract—**Outcome prediction in DeBakey Type III aortic dissections (AD) remains challenging. Large variations in AD morphology, physiology and treatment exist. A patient-specific approach towards a detailed understanding of the distinct features of each single case might be needed to account for this variation. In particular, an improved characterization of hemodynamic parameters in addition to geometrical quantities may yield deeper insight into this complex disease. Advances in cardiovascular magnetic resonance imaging (CMR) have resulted in pulse sequences that provide time-resolved information of blood velocities, aortic wall motion and, with the administration of exogenous intravenous contrast bolus, contrast passage timings.**

Here we provide a combined approach in a group of 10 AD patients using 2D phase contrast magnetic resonance imaging (2D pcMRI) and Time-resolved Angiography With Interleaved Stochastic Trajectories (TWIST) to quantify blood velocities, flow rates, maximum signal enhancement from exogenous contrast and time to maximum signal enhancement in the true lumen (TL) and false lumen (FL). The FL-TL dynamic pressure gradient was derived from 2D pcMRI velocity measurements. These hemodynamic parameters were correlated with dynamic parameters for the intra-arterial septum (IS) wall motion derived from 2D pcMRI.

A strong positive correlation was found between the TL-FL dynamic pressure gradient and maximum IS extension (R=0.76) as well as with maximum IS contraction (R=-0.51) Taking the ratio of maximum extension to maximum contraction, the correlation increased to R= 0.81. The ratio of TL to FL volumetric flow rate showed a high correlation with the difference in FL-TL times to maximum enhancement (R=0.87) illustrating that higher flow in the TL will result in delayed contrast arrival in the FL and vice versa. Analogous, the TL to FL ratio of maximum enhancement correlated with the TL to FL ratio of the maximum volumetric flow rate (R=0.85).

2D pcMRI and 4D MRA in combination with exogenous intravenous contrast bolus allows characterization of hemodynamics in DeBakey type III AD. High correlations between IS wall motion, TL and FL pressure differences, flows and times to maximum enhancement were found. An extension of our analysis to follow-up imaging examinations are warranted to establish the potential for hemodynamic parameters determined with CMR as a marker for clinical outcome in longitudinal studies.

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I. Introduction

Aortic dissections (AD) result from blood entering the intimal layer and splitting the aorta into a true lumen (TL) and a false lumen (FL). It is the commonest life-threatening event involving the aorta affecting 5-10 million people per year [1]. Untreated, 50 % of all AD patients with involvement of the ascending aorta (DeBakey type I and II) die within 24 hours and 60 % of all patient with acute dissection of the descending aorta (DeBakey type III) die within one month. Even after treatment, only 10 % of patients with type I or II and 40 % of patients with type III will be alive after one year. Patients with chronic type III AD are at risk of FL rupture and 20 % of these will require surgical management [1]. One in five patients with a type III AD discharged after successful treatment will die within 3 years [2]. Adverse hemodynamic conditions, leading to partial thrombosis together with occlusion of re-entry tears, are thought to increase FL lumen pressure eventually causing rupture. If conventional medical treatment of type III AD, which focuses on lowering the heart rate through administration of β-blockers, fails and organ malperfusion or lower limb ischemia occurs, surgical intervention is indicated, either through endovascular (TEVAR) stent graft placement across the entry tear thereby lowering inflow into the FL or by fenestration, in which the intra-arterial septum (IS) is ruptured effectively combining TL and FL. Type III AD exhibit a large variety in morphology, with either a straight or tortuous FL, one or multiple entry and re-entry tears, no, partial, or complete thrombosis of the FL. Further, a large variety in dynamic properties, such as IS mobility and TL or FL flow rates have recently been reported [3,4]. The most common used classification separates type III AD into *acute* if presenting less than 2 weeks after symptoms onset, or *chronic*, if presenting after 2 weeks of symptoms onset. Computed tomography (CT) is the most commonly used clinical imaging modality for type III AD, yielding a static picture that cannot display aortic wall motion or hemodynamic quantities. In contrast, dynamic cardiovascular magnetic resonance imaging (CMR), through judicious choice of pulse sequences, provides AD geometry (3D magnetic resonance angiography, MRA), values for TL and FL blood velocities (phase contrast magnetic resonance imaging, pcMRI) and contrast passage times (through

intravenous exogenous contrast administration combined with 4D time-resolved MRA). In a group of 10 type III AD patients, IS wall motion parameters and hemodynamic parameters from dynamic CMR acquisitions were determined and correlated towards a new classification scheme for type III AD combining morphology and hemodynamics.

II. Methods

A. Dynamic CMR Examinations

Approval of the institutional review board was obtained for this study. From 50 patients of the Acute Aortic Treatment Center of the Methodist DeBakey Heart & Vascular Center, 10 were selected for further analysis. CMR examinations (Avanto 1.5 T, Siemens Medical Solutions) included a cardiac gated axial 2D pcMRI acquisition at the location of the diaphragm (TE: 34 - 42 msec, 5 mm slice thickness, 1.4 mm inplane resolution, 150 VENC, one breathhold acquisition) and a 4D MRA acquisition (Time-resolved Angiography With Interleaved Stochastic Trajectories, TWIST, 1.5 mm isotropic voxel resolution, mean temporal resolution 2.4 sec, 30 volumes, 59-65 slices/volume; Optimark bolus administered intravenously). Images were transferred to an offline workstation (Apple, Inc.) for further analysis with ImageJ (NIH).

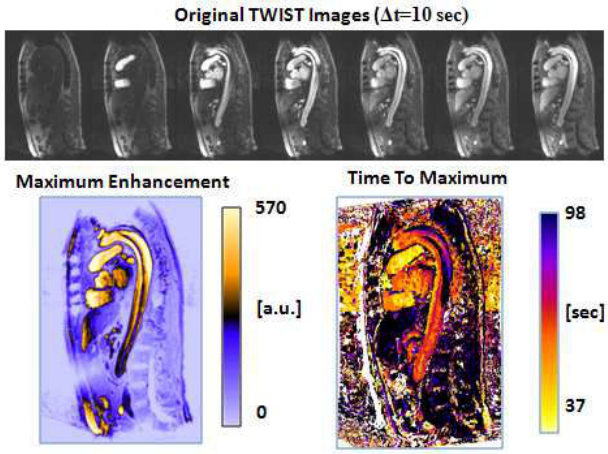

Fig. 1. Top: original TWIST images (displayed every 10 seconds). Bottom: on left: pseudo-color picture of maximum enhancement (arbitrary units), on right: time to maximum enhancement (seconds). Faster enhancement in original TWIST images in TL compared to FL can be appreciated with corresponds to shorter time to maximum (yellow versus orange) in pseudo-color map.

B. Image Postprocessing

1. Aortic Wall Motion Parameters

Aortic wall motion parameters were determined with a method described previously [5]. In short, first TL and FL boundaries were segmented by single value adaptive thresholding from the 2D pcMRI magnitude images after consecutive application of a spatial bandpass filter and a median filter. With the boundary location at the time of minimal aortic flow as baseline, relative extension and contraction of each boundary point was calculated after subtracting the center of mass motion. From these values, the following parameters were derived: maximum extension (d_{max}) and maximum contraction (d_{min}). In addition, the temporal correlation (t_{corr}) of aortic wall displacement with the aortic flow waveform was quantified using the Pearson correlation coefficient.

2. TL and FL Flow and Blood Velocities

For each time point in the cardiac cycle, the TL and FL blood velocities (v_{TL} and v_{FL}) were calculated as the average over all voxels within the TL and FL segmented boundaries (see previous section) taking into account the average signal intensity values from a region of interest in stationary tissue and the VENC value (150 cm/sec). TL and FL volumetric flow rates were obtained by multiplying the velocity values by the cross sectional TL and FL area. Mean flow rates (averaged over the cardiac cycle, f_{TL} and $f_{FL,}$) and maximum flow rates ($f_{max,\ TL}$ and $f_{max,\ FL,}$) were calculated.

3. TL-FL Dynamic Pressure Gradient

The Venturi effect postulates that the velocity of a fluid increases if the cross sectional area of the flow decreases. As a consequence, the static pressure of the increases accordingly. As TL and FL of the type III AD are connected via entry and/or re-entry tears, the sum of their pressures can be considered constant. Accordingly, under consideration of the continuity equation, the TL-FL dynamic pressure gradient ΔP can be estimated by [5]:

$$\Delta P = P_{FL} - P_{TL} = 0.5\rho\{v_{TL}^2 - v_{FL}^2\}$$

with P_{FL} and P_{TL} being the static pressures in the FL and TL, respectively.

The maximum dynamic pressure gradient ΔP_{max} was derived in a similar fashion by replacing v_{TL} and v_{FL} in the equation above by their maximum values for the cardiac cycle.

4. Dynamic CMR Contrast Dynamic Parameters

4D MRA images were reordered from individual image stacks for each time point to individual image stacks for each slice. From the time intensity curves for each voxel in

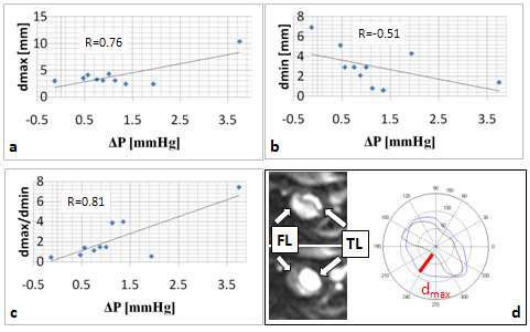

Fig. 2. Correlation plots a: TL-FL dynamic pressure difference (ΔP) versus maximum extension (d_{max}), b: ΔP versus maximum contraction (d_{min}), c: ΔP versus ratio of d_{max}/d_{min}. d: left: axial 2D pcMRI magnitude image at diastole (top) and systole (bottom, TL; true lumen, FL: false lumen, right: TL boundary plots at diastole (black) and systole (blue) in polar plot. In red: distance corresponding to d_{max}.

each slice, TL and FL maximum enhancement ($I_{max,\ TL}$ and $I_{max,FL}$) and time from bolus contrast administration to maximum enhancement ($t_{max,\ TL}$ and $t_{max,FL}$) were determined by a simple search algorithm. Pseudo-color maps were created for each slice for both parameters. I_{max} and t_{max} were derived from these maps at a location corresponding to the slice position for the 2D pcMRI acquisition.

III. Results

A. IS Motion Parameters and Hemodynamic Parameters

Values for IS wall motion parameters and for hemodynamic parameters are listed in table 1. Mean values for d_{max} (3.5 ± 0.9 mm) and d_{min} (3.0 ± 2 mm) were comparable. Mean v_{TL} was approximately a factor 4 larger then v_{FL} (63 ± 16 cm/sec versus 18 ± 11 cm/sec); mean f_{TL} was larger by a factor 5 than mean f_{FL} (59 ± 26 ml/sec versus 12 ± 22 ml/sec). In contrast, $f_{max,TL}$ was only about a factor 2 larger than $f_{max,FL}$ (238 ± 88 ml/sec versus 118 ± 72 ml/sec). $I_{max,\ TL}$and $I_{max,FL}$ were comparable (672 ± 224 and 572 ± 182, repectively) indicating comparable contrast filling of TL and FL, albeit not necessarily at the same time as $t_{max,TL}$ was on average 6 seconds shorter than $t_{max,FL}$ (39 ± 7 sec versus 45 ± 8 sec).

B. Correlation of TL-FL Dynamic Pressure Gradient with IS Wall Motion

A strong positive correlation was found between ΔP and d_{max}: R=0.76. A strong inverse correlation was observed between ΔP and d_{min}: -0.51 (figure 2).Taking the ratio d_{max}/d_{min}, the correlation increased to R= 0.81.

C. Correlation of TL-FL Dynamic Pressure Gradient with Hemodynamic Parameters

A positive correlation between ΔP and $f_{max,TL}$-$f_{max,FL}$ (R=0.45, figure 3) and a negative correlation between ΔP and $t_{max,FL}$-$t_{max,TL}$ were observed (R=-0.30, figure 3).

D. Additonal Correlations between Hemodynamic Parameters

Strong correlations between the ratio f_{TL}/f_{FL} and the difference $t_{max,FL}$-$t_{max,TL}$ (R=0.87) and the ratio $f_{max,TL}/f_{max,FL}$ and the ratio $I_{max,TL}/I_{max,FL}$ (R=0.85) were found.

The remaining pair-wise correlations between the remaining hemodynamic parameters were weak (R<0.25) and are not discussed further.

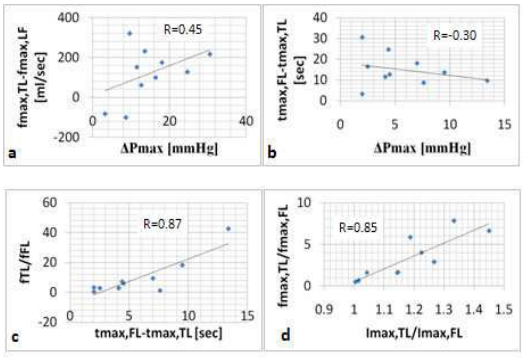

Fig. 3. Correlation plots a: Maximum TL-FL dynamic pressure difference (ΔP_{max}) versus TL-FL difference of maximum flow rate, b: ΔP_{max} versus TL-FL difference of time to maximum enhancement, c: ratio of TL to FL flow rate to TL-FL difference of time to maximum enhancement d: ratio of TL to FL maximum flow rate to ratio of TL to FL maximum enhancement.

TABLE I
HEMODYNAMIC PARAMETERS AND IS WALL MOTION PARAMETERS

Case	1	2	3	4	5	6	7	8	9	10
d_{max}	3.3	4.3	4.1	3.1	2.4	3.0	3.1	5.5	3.5	2.4
d_{min}	2.9	2.9	2.9	2.1	0.6	6.9	0.8	1.4	5.1	4.3
t_{corr}	0.1	0.7	0.2	0.9	0.6	0.8	0	0.1	0.7	0.1
v_{TL}	89	60	69	55	48	40	58	87	50	73
v_{FL}	12	12	13	10	11	28	12	36	7	34
f_{TL}	45	73	47	49	35	23	49	107	85	78
f_{FL}	14	-4	5	-17	28	60	-8	15	-2	27
$f_{max,TL}$	289	280	268	179	93	141	168	328	368	268
$f_{max,FL}$	72	48	93	27	193	223	106	200	47	168
ΔP	0.8	1.0	0.6	0.88	1.4	-0.1	1.1	3.8	0.5	1.9
$I_{max\ TL}$	572	419	630	1128	622	755	341	819	604	831
$I_{max,FL}$	467	353	497	778	619	744	298	714	453	797
$t_{max,\ TL}$	35	35	53	36	39	32	32	47	37	41
$t_{max,FL}$	38	45	60	40	47	34	36	51	50	44

d_{max} and d_{min} in mm, t_{corr} unitless, v_{TL} and v_{FL} in cm/sec, f_{TL}, f_{FL}, $f_{max,TL}$ and $f_{max,FL}$ in ml/sec, ΔP in mmHg, $I_{max,TL}$ and $I_{max,\ FL}$ in arbitrary units, $t_{max,TL}$ and $t_{max,FL}$ in seconds.

IV. Discussion

Towards a better understanding of hemodynamics and IS dynamics in type III AD, hemodynamic quantities and IS motion parameters were determined from 10 patients undergoing dynamic MRI examinations which included 2D pcMRI and 4D MRA.

Applications of 4D MRA for imaging of various vascular beds have been previously reported [6-9]. Johnson et al. utilized an 4D MRA acquisition to develop an automated method of image analysis of the human aorta. With this method, cross-sectional areas along the whole thoracic aorta were obtained within 1% error compared to expert tracing [10]. In an in-vitro study for determining the optimal parameters for 4D MRA applied to renal perfusion imaging, errors in aortic MRI signal intensities (compared to simulated curves created from a tracer kinetic model) were in the order of 5 % for the sequence parameters used in the here described study [11].

In the first part of our analysis, the correlation between the TL-FL pressure gradient and IS motion parameters was investigated. IS maximal extension, maximal contraction and their ratio were found to correlate well with the dynamic TL-FL pressure gradient. This finding supports the hypothesis that IS motion in type III AD may be mainly determined by the force of systolic blood flow. Higher correlation for maximum extension than for maximum contraction (R=0.76 compared to R=-0.51) might be understood if considering that TL velocity is higher and hence the corresponding force exerted on the IS larger

during its extension than FL velocity and corresponding force during its contraction. For the latter, IS composition (collagen content, fiber content, thrombus) may play a larger role in determining IS motion thereby weakening the influence of the TL-FL pressure gradient on the extent of IS motion.

In the second part of the analysis, relationships between hemodynamic quantities derived from the 2DpcMRI acquisition (i.e. blood flow velocities, volumetric flow rates and TL-FL dynamic pressure gradient) and from the 4D MRA acquisition (time to maximum enhancement, signal intensity for maximum enhancement) were investigated. Using ratios of amplitudes or differences of times to peak enabled a lesser dependence on the timing of the bolus acquisition. Largest correlations were found for the difference in TL and FL flow rates versus TL-FL dynamic pressure gradient (R=0.45) and for the difference in FL and TL times to maximum enhancement and the TL-FL dynamic pressure gradient (R=-0.30, inverse relation). While intuitive, i.e. a higher TL flow rate might be expected if a higher dynamic TL dynamic pressure exists and consequently the time to maximum enhancement might be shorter, the found correlations are weak. Potentially, intra-luminal pressure variations along the aorta might be weakening this correlation. These pressure variations were not assessed in the present analysis which included only one axial 2D pcMRI acquisition at the location of the diaphragm.

Ratio of TL to FL volumetric flow rate showed a high correlation with the difference in FL-TL times to maximum enhancement (R=0.87) illustrating that higher flow in the TL will result in delayed contrast arrival in the FL and vice versa. Analogous, the TL to FL ratio of maximum enhancement correlated with the TL to FL ratio of the maximum volumetric flow rate (R=0.85).

In summary, the here presented results obtained with 4D MRA for characterizing the hemodynamics in DeBakey type III AD are encouraging. A study in a larger patient population is warranted to further investigate the relations between dynamic pressure differences, maximum volumetric flow rates and time to maximum signal intensities. Eventually, correlation of our results with follow-up examinations will show if the characterization of AD hemodynamics with 4D MRA may gain significance as a marker for clinical outcome.

V. Conclusion

From dynamic CMR examinations, TL and FL hemodynamics and IS motion were quantified. A strong correlation between the ratio of maximum IS extension to maximum IS contraction and the TL-FL dynamic pressure gradient were found. Ratio of TL to FL maximum enhancement from exogenous intra-venous contrast administration correlated well with ratio of maximum TL to FL flow as did the difference of FL to TL time to maximum enhancement with the ratio of TL to FL mean flow.

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