Title

4D Flow Vorticity Visualization Predicts Regions of Quantitative Flow Inconsistency for Optimal Blood Flow Measurement

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Authors

Contijoch, Francisco J

Horowitz, Michael

Masutani, Evan

et al.

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Title: 4D Flow Vorticity Visualization Predicts Regions of Quantitative Flow Inconsistency for Optimal Blood Flow Measurement

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Summary Statement: Visualization of flow vorticity can highlight regions of flow inconsistency, which may help determine optimal locations for quantification of blood flow with 4D Flow MRI.

Key Points:

1. Flow vorticity can be visualized using an automated pipeline without the need for vessel contouring or particle tracing.
2. Visualization of vortical co-localized spatially and temporally with greater error in blood flow measurements.
3. Vorticity visualization may be used to avoid errors in flow quantification in error-prone regions such as the ascending aorta in patients with aortic aneurysm.

Abstract:

Purpose: To evaluate whether automated vorticity mapping 4D flow MRI can identify regions of quantitative flow inconsistency.

Materials and Methods: In this retrospective study, 35 consecutive patients who underwent MRA with 4D Flow MRI at 3.0T from 12/2017 to 10/2018 were analyzed using a λ_2-based technique for vorticity visualization and quantification. The patients were 58.6 ± 14.4 years old, 12 were women, 18 had ascending aortic aneurysms (maximal diameter > 4.0 cm), and 10 were bicuspid aortic valves. Flow measurements were made in the ascending aorta, mid-descending aorta, main pulmonary artery, and superior vena cava. Statistical tests included T-tests and F-tests with a type I error threshold (α) of 0.05.

Results: The 35 patients were visually classified as having no (n=9), mild (n=8), moderate (n=11), or severe vorticity (n=7). Across all patients, standard deviation of cardiac output in the ascending aorta (aAo) (0.58 ± 0.45 L/min) was significantly ($p<0.001$) higher than in the pulmonary arteries (0.15 ± 0.10 L/min) and descending aorta + superior vena cava (0.14 ± 0.12 L/min). The standard deviation of cardiac output observed in the aAo was significantly greater (p-value < 0.01) in patients with moderate/severe vorticity (0.73 ± 0.55 L/min) than none/mild (0.44 ± 0.26 L/min).

Conclusion: Cardiac output and blood flow are essential MRI measurements in the evaluation of structural heart disease. Vorticity visualization may be used to help guide optimal location for flow quantification.

Introduction

Phase-contrast MRI is the reference standard for non-invasive quantification of blood flow. Both planar phase-contrast (PC) and volumetric phase-contrast (4DFlow) MRI are used assess cardiovascular blood flow by integrating the through-plane component of velocity in a planar region of interest (ROI) (1) and have been validated in a variety of settings (2,3). 4DFlow has recently become clinically-viable with improvements in acquisition time associated with advances in parallel-imaging and compressed-sensing (4). One advantage of 4DFlow is the ability to delineate any number of ROIs from a single volumetric acquisition. This enables retrospective interrogation of flow within multiple vessels or at multiple locations within a single vessel (5).

A natural question that arises in the analysis of 4DFlow data is where measurements should be optimally performed. For example, flow measured anywhere along the ascending aorta (between the sinotubular junction and origin of the brachiocephalic artery) should theoretically be identical via conservation of mass, as given by the continuity equation. However, inconsistency in flow measurements may arise due to either *imaging* or *anatomical* artifacts. For example, a local signal void due to a stent or sternal wire can distort the flow signal and prevent accurate flow measurement. When such an artifact is observed during interpretation, the measurement locations can be adjusted by drawing a different ROI (4DFlow) at an alternate location.

However, it can be more difficult to observe and adjust for *anatomic* causes of flow inconsistency. Inconsistencies in the measured vector field may be due to complex flow

patterns – namely, near a regurgitant valve, stenotic valve, or aneurysmal vessel (6) – and may lack apparent imaging artifacts and may limit the ability of the reader to perceive the underlying cause. Clinically, cardiovascular imagers can try to first identify these scenarios and then adjust measurement locations (7) but the spatial extent of the affected locations may be unclear. Vortical flow – one example of a complex flow pattern – is frequently observed in patients with ascending aortic aneurysm. We hypothesize that locations with flow inconsistencies might be more easily identified by visualizing regions of vortical flow, which may be computed directly from the velocity vector field.

While identification and measurement of vortices in time-varying 3D flow fields is an area of active fluid mechanics research and the field has yet to converge on a single definition or quantitative approach (8), several methods have been proposed for use in 4DFlow (9). λ_2-based estimates (10) have been shown to provide reasonable approximations of vortical regions (11–13). In this paper, we developed a segmentation-free approach to visualize regions of vorticity, analogous to a recently described wall shear stress technique (14). We evaluated whether vortical flow correlated with flow inconsistencies by measuring volumetric blood flow at multiple locations in the cardiovascular system. Furthermore, we compared variations in measured flow to visual assessment of vortical flow regions. We specifically performed our analysis in a population of patients with ascending aortic aneurysm where we have frequently observed flow inconsistencies clinically.

Materials and Methods

Patient Demographics

With IRB approval and waiver of informed consent, we retrospectively evaluated 35 consecutive patients who underwent diagnostic-quality MRA with 4D Flow for evaluation of bicuspid aortic valve, suspected or known ascending aortic aneurysm between 12/1/17 and 10/1/18. The demographics of the patients are shown in Table 1. Maximal orthogonal biaxial aortic measurements were obtained from the 4D Flow MRA. The presence of an ascending aortic aneurysm was defined as a maximal diameter exceeding 4.0 cm. Pediatric patients and patients with congenital heart disease other than bicuspid valve were excluded. Patients with intracardiac and extracardiac shunts were not included.

MRI Technique

4DFlow was performed following administration of intravenous gadolinium contrast (gadobenate dimeglumine, 0.1 mmol/kg). We used a previously-described cardiac-gated, four-point encoded variable-density pseudo-randomly ordered Cartesian sequence followed by iterative compressed-sensing and parallel imaging reconstruction with respiratory self-navigation (4,15) with a 32-channel body receiver coil on a 3T Discovery 750 (GE Healthcare) scanner. The acquired spatial resolution was 1.5 x 1.5 x 3.0 mm with z-direction zero-interpolation filling (ZIP) factor of 2 resulting in 1.5 mm reconstructed slices. 31/35 patients were imaged with a VENC = 250 cm/s while 4 patients were imaged with a VENC of 350 cm/s. All scans were assessed for image

quality by a fellowship trained cardiovascular radiologist. If a study was degraded by patient (motion, metallic hardware) or technical (suboptimal gating, aliasing) factors, it was excluded.

Flow Measurements

Volumetric flow measurements were calculated after background phase correction and delineation of vessel ROIs on the Arterys CardioDL 2.3 (Arterys Inc, San Francisco, CA). Measurements were made at 14 locations by a single reader blinded to vorticity measures. In the ascending aorta aAo, measurements were made at the beginning of the aAo (sinotubular junction, aAo_1), end of the aAo (takeoff of the brachiocephalic artery, aAo_5), and at three equispaced location within the ascending aorta (aAo_{2-4}). Along the mid descending aorta (dAo_{1-3}), three measurements were made centered and equally spaced halfway between the aortic isthmus and the level of the diaphragmatic aortic hiatus. Three measurements were made equally spaced in the main pulmonary artery (mPA_{1-3}) as well as in the superior vena cava (SVC_{1-3}) below the azygos vein.

Mean pulmonary flow measurements and the sum of the mean descending aorta and SVC (dAo + SVC) flows were used as non-aortic measures of cardiac output, which have previously been shown to have high correlation to aortic measurements (16).

Visualization of Vorticity

A segmentation-free approach was developed to visualize regions of vorticity using the λ_2 method (10). Specifically, independently for each time point, we calculated the

velocity gradient tensor and then performed eigenvalue decomposition on $S^2 + \Omega^2$. Pixels with negative λ_2 were multiplied by -1 to become positive and then transformed via logistic function (L=1, k =1 x 10^{-6}, x_o=3 x 10^6) to compress the dynamic range. Values were then multiplied with the magnitude image to mask low signal (e.g. air) regions and subsequently visualized on Arterys software. Vorticity in the ascending aorta was visually scored as none (0), mild (1), moderate (2), or severe (3) by a single reader blinded to measurements of cardiac output. The reader evaluated the entire cardiac cycle and identified the frame with peak vorticity for scoring. Images representative of streamlines, vector fields, vorticity at peak systole for each score are shown in Figure 1. Patients with moderate or severe vorticity were further analyzed to assess whether the vortical region was only in the proximal portion or whether it extended into the distal portions of the ascending aorta.

Volumetric Assessment of Vorticity

To measure vorticity core volume (VCV) at each cardiac phase and observe the change over the cardiac cycle, the vorticity renderings were segmented using ITK-SNAP (Philadelphia, PA) with a fixed binary threshold after logistic transformation (values > 5) (17).

Correlation between Visual and Quantitative Assessment of Vorticity

To evaluate whether the visual assessment of vorticity - which can be easily performed prior to flow quantification – correlates with subsequent segmentation of vorticity core pixels, we compared the visual vortex classification (none, mild, moderate, severe) to

maximum vortical volume (mL) and the temporal integral of the vortical core (mL s) from the entire cardiac cycle.

Correlation between Visual Classification and Differences in Measured Flow

We compared the presence of aneurysm, presence of bicuspid aortic valve, the maximum aortic diameter, cardiac output measured at different locations, and standard deviation of cardiac output between patients with no/mild vorticity to those with moderate/severe.

Statistical Analysis

Statistical analysis was performed with Excel (Microsoft, Redmond WA). For paired data, such as parallel measurements in the same patient, paired two-sided t-tests were with a type I error threshold (α) of 0.05 for statistical significance were performed. For comparison of unpaired data, such as variance in measurements between low (none/mild) and high (moderate/severe) vorticity, F-tests were performed with a type I error threshold (α) of 0.05 for statistical significance. Mean ± standard deviation values are reported for continuous variables.

Results

MRA and Flow Analysis

All 35 patients met inclusion criteria and no studies were excluded due to technical factors. The average aortic diameter was 4.0 ± 0.6 cm/m^2 ranging from 2.5 – 5.2 cm. Indexed to body surface area (BSA), the diameter was 2.1 ± 0.4 cm/m^2 ranging from

1.25 – 2.83 cm/m^2. 18 out of 35 subjects (51%) had aneurysmal ascending aortas with maximum diameter measurement > 4.0 cm. In patients with aneurysmal ascending aortas, the average aortic diameter was 4.5 ± 0.3 cm (index: 2.2 ± 0.3 cm/m^2) while patients without aneurysmal ascending aortas had an average diameter of 3.5 ± 0.5 cm (indexed: 1.9 ± 0.4 cm/m^2). 10 of the 35 patients had bicuspid aortic valves according to echocardiographic reports and/or morphology of aortic valve flow jet by 4D Flow. Other pertinent patient demographic information is shown in Table 1.

Classification and quantification of vorticity core volume

Figure 2 shows flow measured at five positions along the ascending aorta, the standard deviation of these flows, and the vortical core volume measured across the cardiac cycle for two patients. It illustrates high correlation between visual assessment of vorticity and flow inconsistency in the ascending aorta. The 35 patients were visually classified as having no vorticity (n=9), mild (n=8), moderate (n=11), and severe (n=7). Agreement between visual classification of vorticity and vorticity volume are shown in Figure 3. Patients with more severe vorticity upon visualization had significantly higher maximum vorticity volume (3.6 ± 3.6 mL vs 0.5 ± 0.6 mL, $p < 0.001$) as well as higher temporal integral of vortical core volume across the cardiac cycle (12.2 ± 11.3 mL s vs 1.4 ± 1.8 mL s, $p < 0.001$). Of the 18 patients with moderate or severe vorticity, 10 had vortical visualizations that extended into the distal portion of the ascending aorta.

Correlation between Visual Classification and Differences in Measured Flow

Patients with moderate/severe vorticity (n=18) were compared to none/mild (n=17) patients. The impact of visual vortical classification on aneurysm prevalence,

prevalence of bicuspid valve, maximum ascending aortic diameter, flow measures at different locations, and standard deviation of flow measured at different locations is shown in Table 2. 10/18 (55%) of the moderate/severe vorticity patients had aneurysms compared to only 8/17 (45%) of none/mild vorticity patients. This was associated with an insignificant ($p=0.27$) increase in maximum aortic diameters. 9 out of 10 patients with bicuspid aortic valves were classified as having moderate/severe vorticity. 7 patients (out of 10 bicuspid valves and 18 aortic aneurysms) had both bicuspid valves and aortic aneurysms.

Table 2 shows cardiac output measured in the mPA and dAo+SVC were significantly higher in patients with moderate/severe vorticity (but the increase in aAo did not achieve statistical significance). The increase is likely due to differences in patient selection. The standard deviation of cardiac output observed in the aAo was significantly ($p<0.01$) increased in patients with moderate/severe vorticity relative to none/mild while no significant differences were observed in the standard deviation of values measured in the mPA or dAo+SVC ($p>0.64$).

Table 3 illustrates the mean, standard deviations and range in cardiac output observed at the three measurement locations for all patients as well as those with none/mild and moderate/severe vorticity. Across all patients, there were significant differences in CO measured at the aAo and mPA ($p = 0.02$) and aAo and dAo+SVC CI ($p = 0.04$) but not between mPA and dAo+SVC CI ($p = 0.49$). However, these differences were not statistically significant in the vorticity sub-groups ($p > 0.28$) likely due to the small

sample size. Across all patients and sub-groups, the average standard deviation of CO measured in the ascending aorta (aortic valve and 4 ascending locations) was higher than the standard deviation observed in the thee pulmonary artery as well as the standard deviation in the three dAo + SVC measures. Across all groups and in the sub-groups, the absolute and percentage standard deviations in the aAo were significantly ($p<0.006$) higher than values measured from the pulmonary artery and dAo+SVC and there were no significant difference ($p > 0.27$) between pulmonary artery and dAo+SVC values. Across all groups and in the sub-groups, the range of values observes in the ascending aorta was also significantly higher ($p < 0.004$) than values measured from the pulmonary artery and dAo+SVC and there were no significant difference ($p > 0.31$) between pulmonary artery and dAo+SVC values.

In patients with moderate-to-severe vorticity (n=18), the standard deviation of measured CO was significantly ($p=0.02$ on F-test) higher in patients with vorticities that spanned the proximal and distal portion of the ascending aorta (0.44 ± 0.35 L/min, n=10) than in those with only proximal vortices (0.28 ± 0.14 L/min, n=8). The difference in flow between the proximal measure in the ascending aorta (STJ) and the most distal ascending aorta measure was significantly ($p=0.048$) higher (0.94 ± 0.78 L/min) in patients with vorticity throughout the ascending aorta than those with only proximal vortices (0.49 ± 0.35 L/min).

Agreement between measured flow at different locations

As shown in Table 4, flow measured in the mPA and dAo+SVC demonstrated the lowest error and highest Pearson coefficient in the entire cohort. In cases where the aAo flow was compared to a different anatomical location, increased error was observed. The difference between mPA and dAo+SVC was significantly lower than the difference between mPA and aAo for patients with none/mild vorticity ($p = 0.002$) and patients with moderate/severe vorticity ($p = 0.02$). The difference in patients with moderate/severe vorticity did not achieve statistical significance ($p>0.16$).

Discussion:

In this study, we developed an automated approach to visualization of flow vorticity and demonstrated an association between regions with vortical flow and discrepancies in measured cardiac output within and between measurement locations. Specifically, we found that patients with the most severe vortical flow in the ascending aorta also had greatest inconsistency in flow measurement in these same regions. Meanwhile, regions with more laminar flow such as the pulmonary artery, showed greater consistency in flow measurement. This suggests that problems with flow vorticity are earnestly tied and localized to the vessel they are observed in, and do not result in a complete corruption of the entire 4D Flow acquisition. Meanwhile, patients with mild disturbances in the ascending aorta still had flow measurements consistent with surrogate locations, indicating that ascending aortic measurements are not always problematic.

In our study, we used flow measurements quite some distance away from the ascending aorta to highlight these as potential surrogate locations for measurement of cardiac output. The accuracy of this alternative may depend on the presence of laminar flow or confounding artifacts. It may not necessarily be true that these other locations are always better locations for blood flow measurement. For example, cardiac output measured in the pulmonary arteries may also be affected by aneurysmal dilation, as can be seen in severe pulmonary hypertension (18) or long-standing shunts – which can perturb the laminar flow field assumption or affect measurements of blood flow volume. Thus, no single location is guaranteed to be optimal, and clinical judgment and experience is still required to weigh potentially discordant data from different locations.

The location and size of the aortic vortices was rather varied in our patient population. While our results suggest the vortex location can be visualized to be either proximal or throughout the ascending aorta, whether locations within the ascending aorta, distant from a vortex might still be useful to make accurate flow measurements remains unclear. The location, severity, and size of the vortex core may each have an effect. It is also uncertain how to optimally match the visualization of the vortex core to the inconsistencies in the flow vector field. For example, flow measurements in the distal ascending aorta might still be accurate in the setting of a severe but small, proximal vortex. Exploring this further may require not only a much larger patient population, but also a better understanding of how to optimally quantify and display the “size” of the vortex, which is not a well-defined problem from a fluid mechanics standpoint. Future studies may be required to solve this challenging fluid dynamics problem.

A few limitations should be considered. This was a retrospective study performed in 35 patients referred for evaluation of ascending aortic caliber. As a result, cine SSFP was not available for volumetric comparison of cardiac output. However, the accuracy of 4D flow has been previously described (16,19–21). This is a population of patients for whom cardiac output measurements in the ascending aorta are known in our practice to have greater error. We did not observe any vortical flow in the pulmonary arteries in our patient population, which allowed us to use this as a reference point in our study. However, it is unclear vessels in other patient populations are impacted by this phenomenon. We have observed a similar effect of high vorticity when quantifying main pulmonary artery flow in patients with pulmonary hypertension, which is a population of patients that was not explored here. In other words, the relationship between flow vorticity and precise quantification of cardiac output may not be isolated to the ascending aorta. Another limitation is that the impact of flow vorticity on flow measurements may not be equally severe on flow measurements obtained with different MRI platforms and pulse sequences, and there may be specific technical or pulse sequence factors that may mitigate this effect. However, to our knowledge, this relationship has not previously been reported. Lastly, we did not directly correlate a quantitative measure of vortical core volume to the measurement error in the ascending aorta, but relied primarily on visual assessment. Future work may be required to determine optimal methodologies for defining VCV and thresholds where measurement may be too inaccurate to be clinically useful.

In conclusion, the presence of severe flow vortices correlated with greater variance in flow measurements in the ascending aorta. Since phase-contrast MRI serves as the clinical reference standard for non-invasive quantification of blood flow, errors in blood flow quantification may impact patient care and decision-making, and ought to be mitigated. The automated visualization approach proposed here could be used as part of a clinical pipeline to help guide placement of ROIs for blood flow quantification. Flow vortex visualization may help determine if alternative sites should be considered for measurement of blood flow measurement.

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Tables:

Demographic	Value
Age (years)	58.6 ± 14.4 (rg: 28 – 87)
Gender	12 (34%) women
BMI (kg/m^2)	27.6 ± 4.6 (rg: 17.0 – 36.0)
Heart Rate (bpm)	61 ± 13 (rg: 44 – 96)
Ascending Aortic Aneurysm	18/35 (51%)
Bicuspid Aortic Valve	10/35 (29%)

Table 1: Subject Demographics including Age, Gender, BMI, Heart Rate, and presence of ascending aortic aneurysm and bicuspid aortic valve.

	None/Mild Vorticity (n=17)	Moderate/Severe Vorticity (n=18)	P-value
Presence of Aneurysm	8/17	10/18	
Presence of Bicuspid Valve	1/17	9/18	
Maximum Ascending Aorta Diameter /BSA (mm)	2.01 ± 0.47	2.08 ± 0.26	0.27
CO_{aAo} (L/min)	4.82 ± 1.37	5.73 ± 1.99	0.06
CO_{PA} (L/min)	4.83 ± 1.36	6.13 ± 2.01	0.02
$CO_{dAo+SVC}$ (L/min)	4.91 ± 1.35	6.05 ± 1.68	0.02
StD of CO_{aAo} (L/min)*	0.44 ± 0.26	0.73 ± 0.55	<0.01*
StD of CO_{mPA} (L/min)	0.13 ± 0.09	0.17 ± 0.10	0.86*
StD of $CO_{dAo+SVC}$ (L/min)	0.12 ± 0.08	0.15 ± 0.09	0.64*

Table 2: Differences in aortic caliber, bicuspid valve, and cardiac index measurement among patients with low (non/mild) or high (moderate/severe) vorticity. Patients with high vorticity showed greater standard deviation in cardiac index measurements in the ascending aorta than patients with low vorticity. * indicates an F-test was performed on variance values.

Patients	Vessel	μ_{CO} – L/min	σ_{CO} – L/min	σ_{CO} – %	r_{CO} – L/min	r_{CO} – %
All	aAo	5.3 ± 1.8	0.6 ± 0.5	13 ± 16	0.3 – 5.0	5 - 218
	mPA	5.5 ± 1.8	0.2 ± 0.1	3 ± 2	0.1 – 0.6	1 - 16
	dAo + SVC	5.5 ± 1.6	0.1 ± 0.1	3 ± 2	0.0 – 0.8	0 - 18
None/mild Vorticity	aAo	4.8 ± 1.4	0.4 ± 0.3	10 ± 7	0.3 – 2.6	5 – 56
	mPA	4.8 ± 1.4	0.1 ± 0.1	3 ± 2	0.1 – 0.6	1 – 16
	dAo + SVC	4.9 ± 1.4	0.1 ± 0.1	3 ± 2	0.0 – 0.6	0 – 17
Mod/severe Vorticity	aAo	5.7 ± 2.0	0.7 ± 0.6	16 ± 22	0.3 –5.0	6 – 218
	mPA	6.1 ± 2.0	0.2 ± 0.1	3 ± 2	0.1 – 0.6	1 – 14
	dAo + SVC	6.1 ± 1.7	0.2 ± 0.1	3 ± 2	0.1 – 0.8	2 - 18

Table 3: Mean μ, standard deviation σ, and range r (max to min value) in cardiac output measured at multiple locations in the ascending aorta (aAo, n=5), main pulmonary arteries (mPA, n=3), and sum of the descending aorta and superior vena cava (dAo+SVC, n=3). There was greater measurement error in the ascending aorta than the other two locations with increased variation in patients with visualized vorticity.

Patients	Vessel of Interest	Reference	E_{CO} – L/min	ρ_{CI}
All	aAo	dAo + SVC	-0.21 ± 0.70	0.916
	aAo	mPA	-0.20 ± 0.60	0.945
	mPA	dAo + SVC	0.00 ± 0.54	0.959
None/mild Vorticity	aAo	dAo + SVC	-0.09 ± 0.53	0.902
	aAo	mPA	-0.01 ± 0.35	0.910
	mPA	dAo + SVC	-0.08 ± 0.56	0.953
Mod/severe Vorticity	aAo	dAo + SVC	-0.32 ± 0.57	0.921
	aAo	mPA	-0.40 ± 0.36	0.960
	mPA	dAo + SVC	0.08 ± 0.55	0.957

Table 4: Error (E_{CO}) and Pearson coefficient (ρ_{CO}) of cardiac output measured at the ascending aorta (aAo), main pulmonary arteries (mPA), and sum of descending aorta and superior vena cava (dAo+SVC). Across the entire cohort of patients, cardiac output (CO) measurements at the main pulmonary artery and sum of descending Ao and superior vena cava were the two locations that were in greatest agreement.

Figure Legends:

Figure 1: Visualization of streamlines (top), vector fields (middle), and proposed vortex rendering (right) at peak systole in cases of none, mild, moderate, and severe vorticity. All cases except for moderate vorticity had aneurysmal ascending aortas. Flow patterns in the ascending aorta span the spectrum from predominantly laminar to highly vortical. Specifically, vortical flow in the moderate and severe cases (indicated by white arrows) correspond to regions of high vortical rendering above the level of the aortic valve.

Figure 2: Relationship between ascending aortic flow measurements, error, and vortex core volume as a function of the phase of the cardiac cycle for two exemplar patients (left: no vorticity, right: severe vorticity). Top: Flow measurements at five locations along the ascending aorta, Middle: Standard deviation of measured flow, Bottom: volume of the vortex core (VCV) as a function of cardiac phase. Flow measurement error temporally correlates with vortex core volume.

Figure 3: Relationship between visual scoring of vorticity (n=9 for none, n=8 for mild, n=11 for moderate, and n=7 for severe) with maximum Vortex Core Volume (mVCV) and temporal integral of Vortex Core Volume (iVCV).

Figure 4: Difference in measured cardiac output CO for different measurement locations and visualized vorticity in ascending aorta. The mean CO was estimated as the average of the three locations (aAo, MPA, and dAo+SVC). The difference in CO is shown for each measurement at the location (n=5 for aAo and n=3 for MPA and

dAo+SVC). The limits of agreement increased between patients with no/mild vorticity compared to those with moderate/severe from 20.0% to 36.9% in the aAo, 6.0 to 5.4% in the MPA and 5.6 to 6.0% in the dAo+SVC.