Background: The geometry and dynamics of the vena cava are poorly understood and current knowledge is largely based on qualitative data. The purpose of this study is to quantitate the dimensional changes that occur in the infrarenal inferior vena cava (IVC), in response to changes in intravascular volume.

Methods: IVC dimensions were measured at 1 cm and 5 cm below the renal veins, on contrasted computed-tomographic (CT) scans, in 30 severely injured trauma patients during hypovolemic (admission) and fluid resuscitated (follow-up) states. Changes in volume of the infrarenal segment were calculated and correlated with changes in IVC diameter and orientation. The orientation of the infrarenal caval segment was quantified as the angle of the major axis from the horizontal. A representation of the IVC diameter, as would be seen on standard anterior-posterior venographic imaging, was determined by projecting the CT-image of the major axis onto a coronal plane. CT-representations of venographic diameters were compared with measurements of the true major axis to assess accuracy of venograms for caval sizing and filter selection.

Results: All patients had evidence of a collapsed IVC (<15 mm minor axis dimension) on admission. Mean time between admission and follow-up CT was 49.5 (range: 1-202) days. The volume of the infrarenal segment increased more than twofold with resuscitation, increasing from 6.9 ± 2.2 (range: 3.1-12.4) mL on admission, to 15.7 ± 5.0 (range: 9.2-28.5) mL on follow-up (P < .01). At both 1 and 5 cm below the renal veins, the IVC expanded anisotropically such that the minor axis expanded up to five times its initial size accommodating 84% of the increased volume of the segment, while only small diameter changes were observed in the major axis accounting for less than 5% of the volume increase (P < .001). Further, the IVC was left-anterior-oblique in all patients, with the major axis 26 degrees off the horizontal on average. This orientation did not change significantly with volume resuscitation (P > 0.5). The obliquity of the IVC resulted in significant underestimation of caval size of up to 6.8 mm, when using the venographic representation for sizing instead of the true major axis (P < 0.001).

Conclusions: In response to changes in intravascular volume, the IVC undergoes profound anisotropic dimensional changes, with greater displacement seen in the minor axis. In addition, the IVC is oriented left-anterior oblique and caval orientation is not altered by changes in volume status. IVC obliquity may result in underestimation of caval size by anterior-posterior venogram. (J Vasc Surg 2009;**:**:**.)
scan within the first hour of admission to the hospital, during initial period of hypovolemia, and a follow-up abdominal CT scan more than 24 hours after admission, when initial fluid resuscitation was complete. Patients were excluded if CT scans obtained at either time-point, were completed without the use of intravenous contrast, or if slice thickness was greater than 5 mm.

**Measurements.** Vena cava dimensions were measured using a Vista Imaging Viewer (Vital Images Inc, Minnetonka, Minn), in each patient, on the initial and follow-up CT scans, at 1 cm and 5 cm below the lowest renal vein, corresponding to the most common location for IVC filter placement. Diameters were measured and recorded from the center of the lumen in the major and minor axis in an orthonormal view (Fig 1). Lumen contour was traced on axial CT scan images and cross-sectional area was calculated quantitatively in mm². Volume of the infrarenal IVC was calculated from area and diameters according to Smalian’s formula for calculating volume of a tapered elliptical cylinder¹¹ (Fig 2).

On standard axial CT images the obliquity of the IVC was measured as the angle between the major axis and the horizontal (Fig 3). Utilizing the standard axial CT images, we assumed the venographic diameter to be equivalent to the horizontal line as this is the view that would be seen on standard anterior posterior view seen under fluoroscopy. However, angle corrected orthonormal views on CT would be the true representation of the major axis.
Table I. Diameter changes in the major and minor axes of the IVC in response to changes in intravascular volume status

<table>
<thead>
<tr>
<th>IVC dimension</th>
<th>IVC diameter (mm)</th>
<th>IVC diameter (mm)</th>
<th>Diameter change (mm)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>admission-hypovolemic</td>
<td>follow-up-resuscitated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 cm below renals</td>
<td>9.2 ± 3.0 (3.9-14.9)</td>
<td>16.8 ± 4.1 (10.2-27.2)</td>
<td>7.6 ± 4.4 (-0.2-17.4)</td>
<td>P &lt; .001</td>
</tr>
<tr>
<td>5 cm below renals</td>
<td>10.9 ± 3.2 (3.3-16.8)</td>
<td>17.3 ± 3.7 (9.6-25.4)</td>
<td>6.4 ± 4.4 (0.6-13.8)</td>
<td>P &lt; .001</td>
</tr>
<tr>
<td>Major axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 cm below renals</td>
<td>24.9 ± 3.9 (14-30.5)</td>
<td>26.7 ± 3.8 (21-38.1)</td>
<td>1.8 ± 2.7 (-4.7-7.8)</td>
<td>P &lt; .001</td>
</tr>
<tr>
<td>5 cm below renals</td>
<td>23.5 ± 2.5 (20-29.3)</td>
<td>24.7 ± 2.1 (21.4-29.1)</td>
<td>1.2 ± 2.3 (-2.3-6.4)</td>
<td>P &lt; .001</td>
</tr>
</tbody>
</table>

IVC, Inferior vena cava; CT, computed-tomographic.

Significant diameter increases are seen in both the major and minor IVC axes although it is anisotropic, with greater expansion in the minor axis.

To be the true representation of the major axis. The maximum horizontal line measured on the standard axial CT images, which represented venographic diameters, were compared with orthonormal diameters of the major axis to assess accuracy of filter sizing by venogram. No measurements of the actual venograms were available for comparison to our assumed measurements or the orthonormal measurements of the major axis.

Statistics. Results are expressed as the mean ± standard deviation. All measurements were independently reviewed by two observers blinded to the timing sequence of the CT scans, to evaluate repeatability between and among observers. Changes in diameter, caval orientation, and volume were evaluated using a Student t test for paired data. Linear regression was used to correlate changes in diameter and volume. Analyses of measurement method comparison data according to Bland and Altman were performed to analyze repeatability.

RESULTS

Patients. Between March 2003 and March 2006, 559 patients underwent IVC filter placement at Parkland Memorial Hospital using venographic and fluoroscopic image guidance. Of these, 30 trauma patients met the inclusion criteria of this study with TISS scores of greater than 25, abdominal CT scans obtained within an hour of admission during initial hypovolemia, and follow-up abdominal CT scans completed more than 24 hours later after initial resuscitation. All CT scans were obtained per trauma protocol with intravenous contrast and 5 mm slice thickness.

Mean patient age was 32 ± 11.5 (17-57) years and there was a male predominance (n = 28; 93%). Mean trauma injury severity score was 40.2 ± 13.1 (34-75), demonstrating the severity of patient injuries. All patients had evidence of a collapsed IVC (<15 mm minor axis dimension), consistent with hypovolemia, on admission CT imaging. Mean time between admission (hypovolemic) and follow-up (fluid resuscitated) CT scans was 49.5 days (range: 1-202 days). On follow-up CT scans, all patients had evidence of IVC expansion, with an increase in both the volume and diameter of the infrarenal segment, consistent with volume resuscitation.

IVC volume. The mean volume of the IVC segment on admission was 6.9 ± 2.2 mL (range: 3.1-12.4 mL) and increased to 15.7 ± 5.0 mL (range: 9.2-28.5 mL) (P < .001) on follow-up imaging. This represents more than a twofold increase in volume of the infrarenal IVC between scans, consistent with initial hypovolemia and subsequent resuscitation. Quantitative assessments of IVC segment volume were consistent between the two observers, with no significant differences within or between observers. The interobserver repeatability coefficient was 13 mL. The intraobserver repeatability coefficients were 9 mL for observer 1 and 10 mL for observer 2.

IVC diameter. Vena cava diameters in the hypovolemic and fluid resuscitated states are shown in Table I. Movement of the infrarenal IVC in response to segmental volume changes was anisotropic, with greater movement seen in the minor axis compared with the major axis (Figs 5 and 6).

At 1 cm below the renal veins, in the minor axis, the mean diameter of the IVC increased almost twofold after fluid resuscitation, from 9.2 to 16.8 mm (P < .001). In the most extreme cases, the minor axis increased nearly five times its initial size after fluid resuscitation. Similarly, 5 cm below the renal veins, the mean diameter of the minor axis of the IVC increased from 10.9 to 17.3 mm after fluid resuscitation (P < .001). The largest diameter increases at this location, resulted in expansion of the minor axis to 3.5 times its initial size.

While the major axis of the IVC also increased significantly after fluid resuscitation, the magnitude of the increase was much less. At one cm below the renal veins, the major axis increased only 7% on average, from 24.9 to 26.7 mm (P < .001) and 5 cm below the renal veins, the major axis increased only 5% on average from 23.5 to 24.7 mm (P < .001). Further, movement of this axis was more variable, with some patients experiencing shortening of this axis and others experiencing expansion of this axis with fluid resuscitation. Maximum diameter changes at 1 cm below the renal veins ranged from a 16% decrease in diameter in one subject to a 55% increase in diameter in another. Maximum diameter changes at 5 cm below the renal veins ranged from a 6% decrease in diameter in one subject, to a 43% increase in diameter in another.

Overall, in response to a greater than twofold increase in volume of the infrarenal IVC segment, 71% of patients had a greater than 10 mm increase in diameter of the minor axis while 77% of patients experienced less than 2 mm of
movement in the major axis. By linear regression, increase in the diameter of the minor axis accommodated 84% of the increase in volume of the infrarenal IVC ($r^2 = 0.84$). Expansion of the major axis accommodated only 4% ($r^2 = 0.04$%) of the volume increase in the infrarenal IVC.

Quantitative assessments of diameters from CT scan images were consistent between the two observers, with no significant differences within or between observers. The interobserver repeatability coefficient was 1.0 mm. The intraobserver repeatability coefficients were 0.7 mm for observer 1 and 0.9 mm for observer 2.

**IVC orientation.** The major axis of the IVC was oriented left-anterior-oblique (LAO) in all 30 patients. The angle of obliquity of the major axis, at both 1 and 5 cm below the renal veins, was approximately 26 degrees from the horizontal, as shown in Table II. However, this axis was as much as 44 degrees from the horizontal in some patients.

The oblique orientation of each patient’s vena cava did not change significantly between the admission and follow-up CT scans indicating that the obliquity of the infrarenal vena cava segment remains stable during volume changes (Fig 7). Further, the placement of an IVC filter in the interval between the initial and follow-up CT scan in 21 patients (70%), did not significantly change the obliquity of the IVC.

Quantitative assessments of the obliquity of the IVC from CT scan images were consistent between the two observers, with no significant differences within or between observers. The interobserver repeatability coefficient was 0.9 degrees. The intraobserver repeatability coefficients were 0.7 degrees for observer 1 and 0.5 degrees for observer 2.

**Venacavographic diameter.** The obliquity of the IVC resulted in a discrepancy between maximum caval diameter determined by actual measurement of the major axis and that determined by measurement of the major axis projected onto the horizontal plane, as would be visualized on standard anterior-posterior venogram (Fig 8). On average, the venacavographic representation undersized the cava by 1 to 2 mm but in some patients, this discrepancy was as great as 6.8 mm, corresponding to a 28% underestimation in caval size (Table III). The degree to which the venogram underestimated caval size was directly dependent on the degree of obliquity of the cava. The greater the oblique angle of the IVC, the greater the discrepancy noted between the true diameter of the IVC and the CT venographic diameter representation.
Quantitative assessments of CT representation of the venographic diameter were consistent between observers, with no significant differences detected within or between observers. The interobserver repeatability coefficient was 0.7 mm. The intraobserver repeatability coefficients were 0.5 mm for observer 1 and 0.7 mm for observer 2.

**DISCUSSION**

The IVC is a responsive and dynamic capacitance blood vessel. The high compliance of the caval wall allows its size and geometry to fluctuate in response to relative and absolute intravascular volume changes. The cava is exposed to relative volume changes during quiet respiration and Valsalva maneuvers. During inspiration, as negative pressure draws blood from the IVC into the chest, partial collapse of the IVC is observed. During expiration, and traditionally during Valsalva maneuvers, positive intrathoracic pressure impedes blood flow into the chest, resulting in a relative increase in caval volume and IVC expansion.\(^{12,13}\)

The IVC responds in a similar manner to absolute changes in intravascular volume status of the subject. A decrease in circulating blood volume, which may be observed with dehydration, shock, sepsis, and hemodialysis, will result in at least partial caval collapse. Even small changes in intravascular volume, observed with blood donations of 450 cc, have been shown to result in significant reductions in caval diameter.\(^{14}\) Conversely, an increase in circulating blood volume, observed with decompensated heart failure or blood transfusions, results in IVC expansion.\(^{14-22}\)

While many authors have provided qualitative evidence of the diameter variation that occurs in the IVC during respiration and shifts in intravascular volume as described above, quantitative descriptions of the dynamic geometry and orientation of the IVC have been lacking. Recently, the first quantitative analysis of the wall motion of the infrarenal cava during respiration and Valsalva maneuvers was performed using intravascular ultrasound.\(^{10}\) This is the first quantitative analysis of the dynamic changes in IVC geometry and orientation that occur in response to changes in intravascular volume. Notably, it is also the first report to quantify the orientation of the caval axis. While prior re-

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**Table II.** Obliquity of the IVC expressed as the angle between the major axis and the horizontal

<table>
<thead>
<tr>
<th></th>
<th>Hypovolemic IVC</th>
<th>Volume resuscitated IVC</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm below renals</td>
<td>25.8 ± 7.5 (9.9-37.8)</td>
<td>25.9 ± 7.7 (12-39.6)</td>
<td>.93</td>
</tr>
<tr>
<td>5 cm below renals</td>
<td>27.2 ± 6.7 (11.8-39.8)</td>
<td>25.7 ± 8.2 (6.6-43.8)</td>
<td>.53</td>
</tr>
</tbody>
</table>

IVC, Inferior vena cava; LAO, left-anterior-oblique.

Note that the orientation of the IVC was left-anterior-oblique in all patients and thus angles are expressed as degrees LAO from the horizontal. Note also, that the obliquity of the infrarenal IVC remains stable regardless of segment volume changes.

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**Fig 6.** Anisotropic movement of the inferior vena cava (IVC). Images above represent the same individual’s IVC in the hypovolemic (images left) and resuscitated (images right) states. When looking at the frontal view of the IVC, which visualizes a reflection of the major axis, the IVC looks identical in the hypovolemic and resuscitated states. However, when looking at the lateral view, which visualizes a reflection of the minor axis, it is observed that in fact, the minor axis of the IVC is collapsed during hypovolemia and expanded after initial resuscitation. This anisotropic movement is also seen in the axial images obtained at 1 cm (images above) and 5 cm (images below) below the renal veins.
Fig 7. Obliquity of the inferior vena cava (IVC). The major axis of the IVC was oriented left-anterior oblique in all patients. Each row above represents the infrarenal IVC of one patient, at the same location, on admission (image left) and follow-up (image right) computed-tomographic (CT) imaging. Note that the orientation of the infrarenal IVC remains constant in both patients, regardless of apparent increases in intravascular volume status between scans.

Fig 8. Venographic diameters. Representations of the maximum diameter of the inferior vena cava (IVC), as would be seen on standard anterior-posterior venogram, were compared with measurements of the maximum diameter of the IVC in the major axis on orthonormal axial computed-tomographic (CT) images. Due to the oblique lie of the IVC, the venographic representations consistently undersized the IVC, compared with the true maximum IVC dimensions.
ports have occasionally referred to the obliquity of the cava, the literature has failed to quantify this finding.

By studying serial CT scans obtained in severely injured trauma patients at admission and during follow-up (>24 hours after admission), we were able to identify patients with large changes in volume of the infrarenal IVC, the most common location for IVC filter fixation. Consistent with clinical evidence of hypovolemia, all patients in this study had CT evidence of a collapsed IVC on admission (<15 mm in the minor axis dimension at one centimeter below the renal veins). Following fluid resuscitation, all patients had evidence of IVC expansion, with a significant increase in minor axis diameter and a significant increase in the volume of the infrarenal vena cava segment on follow-up CT imaging, consistent with fluid resuscitation.

We found that the IVC undergoes profound anisotropic dimensional changes in response to intravascular volume shifts, with significantly greater diameter changes seen in the minor axis compared to the major axis. In fact, in 77% of the patients in this study, movement of the major axis was less than 2 mm after volume resuscitation while 71% of patients had a greater than 10 mm increase in diameter of the minor axis. While prior study has shown that the minor IVC axis may expand up to 10% during quiet expiration and up to 30% during valsala,10 we found that the magnitude of diameter changes in inferior vena cava can be much larger in response to changes in intravascular volume. We noted that the minor axis can expand up to five times (500%) its original, collapsed diameter during volume resuscitation. This magnitude of change in vena cava dimensions may have an impact on the stability of implanted vena cava filter devices. Although we were not able to correct for respiratory variation between CT scans in this study, the profound dimensional changes that we found in relation to intravascular volume changes, far exceeded the expected changes that are reported to occur during respiration.

In addition, we have demonstrated that despite significant dimensional changes observed in the infrarenal IVC with volume resuscitation, patient-specific caval orientation remained constant, for each patient, as it collapsed and expanded. The major axis of the infrarenal cava was oriented 26 degrees left-anterior-oblique, with respect to the horizontal, on average, with a maximum obliquity of nearly 50 degrees left-anterior-oblique. Further, while 70% of patients had IVC filters placed in the interval between CT scans, the presence of the filter had no effect on the dynamic geometry or orientation of the infrarenal IVC. In all patients, regardless of IVC filters, volume expansion between scans resulted in significant expansion of the minor axis while the major axis and overall caval orientation remained relatively stable. It is important to note that our findings differ from prior reports that IVC filters cause a predictable, circular deformation of the cava with foreshortening of the major axis and straightening of the IVC axis into a horizontal plane.24,25

The oblique lie of the cava may also have important clinical implications for the placement of IVC filters. The development of small percutaneous sheaths has resulted in the ability to place filters under venacavographic image guidance. Cavography provides accurate delineation of the renal veins and allows identification of anatomical venous variations, intraluminal thrombus and external caval compression. Measurement of caval size, however, is limited by the two-dimensional imaging produced with cavography. Standard anterior-posterior venography does not image in the plane of the major axis but instead, images in an axis horizontal to the table. The venacavographic diameter, therefore, is merely a reflection of the major axis. Use of standard venographic measurements for caval sizing may, therefore, result in a significant underestimation of the true maximum caval diameter.24,26

Our data suggest that contrasted CT scans obtained with axial cuts through the IVC, viewed in an orthonormal plane may be more reliable than venography for caval sizing prior to IVC filter selection. CT likely provides more accurate identification and measurement of the true maximal diameter of the vena cava, in its major axis. In addition to more precise diameter measurements, CT is more sensitive than cavography in detection of venous anomalies.23,27

Transabdominal ultrasound and intravascular ultrasound may also provide alternative options for accurate caval sizing in patients who do not have CT scans completed prior to filter placement or are not candidates for contrasted CT scans because of renal insufficiency or contrast allergies. Both techniques can provide visualization of axial IVC images, allowing measurement of both the minor
and major axis. However, both techniques are also associated with their own set of limitations and accuracy of these techniques for IVC sizing has not been established.

The findings from this study provide insight into the dynamic geometry and orientation of the infrarenal IVC and further study is now indicated to determine the clinical significance of these findings. As all currently approved IVC filters rely on hooks engaged within the IVC wall for fixation and device stability, the profound nonuniform movement of the IVC wall may have implications for IVC filter design, fixation, fatigability, and clinical outcomes associated with IVC filter use. Likewise, the orientation of the cava may have implications for diagnostic and procedural imaging of the IVC.

**AUTHOR CONTRIBUTIONS**

Conception and design: EM, FA, CZ

Analysis and interpretation: EM, FA, TF, CZ

Data collection: EM, TF, VP

Writing the article: EM, FA, CZ

Critical revision of the article: EM, FA, TF, CZ, CT, VP

Final approval of the article: EM, FA, TF, CZ, CT, VP

Statistical analysis: EM, VP

Obtained funding: Not applicable

Overall responsibility: CZ

**REFERENCES**


**DISCUSSION**

Dr Marc A. Passman. I would like to congratulate Dr Murphy and her coauthors on a very nice presentation and manuscript. Of course, with their presentation today, we are reminded of Ferdinand Magellan who in 1519 set out from Spain to circumnavigate our flat Earth, thereby proving the Earth is indeed round. Fortunately for us, Dr Murphy and her coauthors do not view our vascular planet as flat or round. A few years ago at the Thirty-first Annual Meeting of the Southern Association for Vascular Surgery in Puerto Rico and subsequently published in the Journal of Vascular Surgery in 2007, the same authors presented on anisotro-
pic deformation of the infrarenal aortic neck with the cardiac cycle. Today, through those same anisotropic glasses, we learn that the inferior vena cava is sometimes flat, sometimes round, but mostly elliptical, sitting in an oblique orientation and changing diameter based on intravascular volume changes, more so in the minor axis than the major axis. The authors suggest that these geometric changes and spatial orientation may have important implication both for vena cava filter design and placement.

There are some flaws that should be noted in their study design – Such as lack of confirmation of volume status either with concurrent fluid resuscitation data or central venous pressure measurements, limitations of static computed-tomographic (CT) imaging and reprocessing at variable time intervals after initial CT scan, and lack of correlation with dynamic imaging such as intravascular ultrasound (IVUS) to show real-time changes in vena cava geometry with each cardiac pulsation and respiratory cycle. Regardless of these shortcomings, I do agree that the observations presented today may have some importance in understanding the relationship of the vena cava volumetric capacitance and the filters we use. However, I would dissuade any additional conclusions that this observation predisposes to filter migration or fatigue-related filter complications, as this leap is not supported by their study design.

I have two questions. First, what is the best way to measure the inferior vena cava for intended filter placement? All current filter indications for use (IFU) refer to the maximum vena cava diameter, which in some respects, corresponds to your major axis measurement. Others have suggested, somewhat analogous to aortic stent graft sizing, that the minor axis may be more important to insure that the base diameter of the filter is within a critical range for attachment. Should we make cross-sectional area or volumetric calculations as done in your study, or additional vena cava circumference measurements, which are independent of vena cava shape and may be more accurate to determine maximum filter base capacity? As observed in your study, with intravascular volume change there is indeed change in both the major and minor axis, but how much did the vena cava circumference or cross-sectional area change at the intended filter base attachment level?

Second, the currently available FDA approved filter devices fall into three general categories when it comes to their relationship with the vena cava – Those that conform with the vena cava shape (such as conical filter designs which have a circular base when viewed ex vivo, but tend to take on the vena cava geometry at the filter base in vivo); Those that are more rigid (such as the double basket filter designs), which tend to increase the diameter of the vena cava at the attachment level; and those designs that do a bit of both. For those of us who place filters with intravascular ultrasound, geometric changes are often observed immediately after filter placement reflecting the combination of conformability and radial strength for current filter design. Some of your study population had filters placed prior to the follow-up CT scan, but these patients are lost in the larger analysis. Did you perform a subgroup analysis evaluating the impact of the filters placed on the vena cava geometry independent of volume changes? I would suspect if you test your hypothesis, you would find that current filter designs perform just fine within a certain acceptable vena cava geometric and volumetric range, but that design performance will begin to deteriorate at some maximum end-point that still needs to be better defined.

Again, I appreciate the opportunity to comment on a very nice paper. Thank you.

Dr Murphy. Dr Passman, thank you for your insightful comments. Magellan did indeed prove that the Earth is round and interestingly our study showed that the inferior vena cava (IVC) is not.

In regards to your questions about our study design, the retrospective nature of this report did not allow confirmation of the subject’s volume status with concurrent resuscitation or central venous measurements. Nonetheless, we were able to demonstrate an increase in IVC segment volume between scans, which has been shown to correlate closely with intravascular volume status. You also correctly pointed out that we were not able to adjust for respiratory and cardiac variation in IVC dimensions between CT scans although, I would like to note that the profound dimensional changes that we found in relation to intravascular volume changes, far exceeded the expected changes that are reported to occur during the respiratory and cardiac cycle.

We agree that while we have not proved a direct relationship between the dimensional changes of the IVC and the occurrence of filter migration or complications, the magnitude of change is such that one might anticipate a relationship. Studies to determine the clinical significance of our findings are now indicated.

For filter sizing, I believe that using measurements of the maximal caval diameter, in the major axis is best. I do not think that measurement of the minor axis diameter, caval circumference or IVC area would improve the accuracy of filter selection, at least not with currently available filter designs. With this in mind, I believe that CT is probably more accurate than venogram for vena caval sizing. CT provides accurate identification and measurement of the true maximal diameter of the vena cava, in its major axis. Other imaging options that allow for visualization of the major axis of the IVC include preoperative transabdominal ultrasound or intraoperative IVUS. Still, further data is needed to directly compare the accuracy of available imaging modalities for caval sizing.

Lastly, you asked about the geometric changes observed in the IVC following filter placement. You are correct that 70% of our patients had IVC filters placed in the time interval between CT scans. IVC filter placement did not appreciably change the patient-specific caval orientation or the geometry of dimensional changes observed in the IVC in response to volume resuscitation. One poignant example was seen in a septic patient whose CT scan revealed almost complete collapse of the IVC and accompanying filter along the minor axis. This filter clearly had no effect on the volumetric driven changes in caval geometry in this patient. However, since all filters observed in this study were conical, I cannot comment on the impact of more rigid filter designs on caval geometry in relation to intravascular volume changes.

Thank you again for your comments, well-thought questions and attention to our manuscript.