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PERITONEUM

# A comparison of segmented abdominopelvic fluid volumes with conventional CT signs of abdominal compartment syndrome in a trauma population

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## Abstract

**Purpose** To compare the utility of abdominopelvic fluid volume measurements with established computed tomography signs for refractory post-traumatic abdominal compartment syndrome.

**Methods** This retrospective observational cohort study included 64 consecutive adult trauma patients with preoperative CT and diagnosis of refractory abdominal compartment syndrome requiring decompressive laparotomy at a level I trauma referral center between 2004 and 2014. We hypothesized that abdominal fluid volume measurements would be more predictive of the need for early laparotomy than previously described conventional CT signs of refractory ACS. Abdominopelvic fluid volumes were determined quantitatively using semi-automated segmentation software. The following conventional imaging parameters were recorded: abdominal anteroposterior:transverse ratio (round belly sign); infrahepatic vena cava diameter; distal abdominal aortic diameter; largest single small bowel wall diameter; hydronephrosis, inguinal herniation; and mesenteric and body wall edema. For outcome analysis, patients were stratified into two groups: those who underwent early (< 24 h) and late (≥ 24 h) decompressive laparotomy following CT. Correlation analysis, comparison of means, and multivariate logistic regression were performed.

**Results** Abdominal fluid volumes ($p=0.001$) and anteroposterior:transverse ratio ($p=0.009$) were increased and inferior vena cava diameter ($p=0.009$) was decreased in the early decompressive laparotomy group. Multivariate analysis including conventional CT variables, fluid volumes, and laboratory values revealed abdominal fluid volumes ($p=0.012$; Δ in log odds of 1.002/mL) as the only independent predictor of early decompressive laparotomy.

**Conclusions** Segmented abdominopelvic free fluid volumes had greater predictive utility for decision to perform early decompressive laparotomy than previously described ACS-related CT signs in trauma patients who developed refractory abdominal compartment syndrome.

**Keywords** Abdominal compartment syndrome · Trauma · Computed tomography · Quantitative imaging · Abdominopelvic fluid volume

## Introduction

Abdominal compartment syndrome (ACS) is a severe complication of abdominal surgery, sepsis, and trauma [1] and remains an important cause of lethality in trauma patients [2–4]. Refractory ACS requiring decompressive laparotomy and management of the open abdomen is heralded clinically by abdominal distension, oliguria/anuria, decreased cardiac output, increased peak airway pressures, increased bladder pressures, increased lactate level, and acidosis [1, 5–7]. Delays in performing decompressive laparotomy exacerbate organ failure and increase mortality [1, 2, 8, 9]. Surgical decompression within the first 24 h of onset plays a protective role [10]. Computed tomography (CT) is frequently performed early in the course of ACS progression. Presently, the ratio of maximal anteroposterior to transverse abdominal dimensions (AP:T ratio) is the only semi-quantitative

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imaging parameter used to assess ACS severity. A ratio greater than 0.8 is predictive of refractory ACS and referred to as the "round belly sign" [11]. Additional binary and categorical CT markers include inferior vena cava (IVC) compression, renal compression/displacement, hydronephrosis, ascites, hemoperitoneum, peritoneal versus retroperitoneal fluid accumulation, and inguinal herniation [11–13].

Quantitative assessment of abdominopelvic fluid volumes can be performed using semi-automated seeded region growing segmentation tools, a feature of commercial post-processing software from a variety of vendors [14–16]. Segmented abdominopelvic fluid volume measurements may represent a highly granular imaging biomarker for refractory ACS. We directly compared the utility of abdominopelvic fluid volume measurements with conventional CT signs in a population of trauma patients who developed refractory ACS requiring decompressive laparotomy. Patients were stratified into two groups—those in which decompressive laparotomy was performed within 24 h following CT, and those in which decompressive laparotomy was performed after 24 h. CT markers of ACS were compared using tests for proportions, comparison of means, and multivariable logistic regression.

## Materials and methods

### Patient characteristics

This HIPAA-compliant retrospective analysis of a prospective cohort from a single, large-volume regional Level I trauma center was approved and defined as minimal risk by the institutional review board, with the need for informed consent waived. Query of the trauma registry identified consecutive patients age 18 or older presenting to our trauma center from October 1, 2004 through December 31, 2014 with abdominopelvic trauma, a preoperative diagnosis of refractory ACS that required decompressive laparotomy, and pre-operative CT. Pre-operative diagnosis of refractory ACS was based on a combination of factors including elevated bladder pressures, tense abdomen on exam, and clinical or laboratory evidence of end organ failure. ACS was listed as the post-operative diagnosis in every patient's operative report. Operative notes typically described rapid evisceration under pressure following incision of the peritoneum. Patients were excluded if preoperative CT was unavailable ($n = 51$) or if laparotomy was performed for exploration and organ repair or hemostasis rather than decompression ($n = 14$; splenectomy in five patients; hollow visceral perforation in nine patients). The final study cohort was composed of 64 patients (age $43.2 \pm 17.8$ years; 50/64 male). Demographic information was retrieved from the trauma registry (Table 1). Patients were stratified into two groups—those who underwent early decompressive laparotomy (< 24 h following CT, $n = 28$) or late decompressive laparotomy ($\geq$ 24 h following CT, $n = 36$) [10].

### CT technique

Patients routinely underwent contrast-enhanced abdominopelvic CT from the dome of the diaphragm to the greater trochanters on a 16-section CT system (Brilliance 16 Power; Philips Medical Systems, Cleveland, OH, USA) during the period between 2004 and 2008, and 40- or 64-section (Brilliance, Phillips Healthcare, Andover, MA, USA) multidetector CT units thereafter. Images through both the abdomen and pelvis were acquired in either the portal venous phase or late arterial phase. We used the portal venous phase in 42 of 64 patients for interpretation and measurement, and arterial phase images in 16 patients. Six of the 64 patients received no intravenous contrast. Images were archived at 3–5-mm section thickness.

### Imaging analysis

All CT studies were uploaded to our post-processing thin-client (Aquarius iNtuition TeraRecon, Foster City, CA,

**Table 1** Demographic characteristics

| Covariate | Total Cohort $n = 64$ | Early DCL $n = 28$ | Late DCL $n = 36$ | $p$ value |
|---|---|---|---|---|
| Age (mean[SD]) | 43.2 (17.8) | 46.3 (20.0) | 40.8 (15.8) | 0.34 |
| Sex (male) {$n$[%]) | 50 (78.1) | 21 (75) | 29 (80.5) | 0.87 |
| Mortality | 35 (54.7) | 16 (57.1) | 19 (52.8) | 0.8 |
| Injury severity score (median[IQR]) | 33.5 (25–41) | 33.5 (22–41.5) | 32 (25–41) | 0.76 |
| Mechanism of injury ($n$[%]) | | | | 0.31 |
| Blunt | 58 (90.6) | 24 (85.7) | 34 (94.4) | |
| Penetrating | 5 (7.8) | 3 (10.7) | 2 (5.6) | |
| Other | 1 (1.6) | 1 (3.6) | 0 (0.0) | |

*SD* Standard deviation, *IQR* Interquartile range, *DCL* decompressive laparotomy

USA) for independent blinded review by multiple readers (two attending trauma radiologists with 5 and 10 years of trauma radiology experience (DD and UKB respectively), and one abdominal imaging trained attending radiologist with 2 years of experience (AW).

All three readers performed an assessment of binary and categorical signs. Additionally, the junior-most trauma radiologist (DD) measured quantitative imaging signs including: AP:T ratio and infrahepatic IVC diameter (with measurements taken at the level of the renal vein inflow [11]), aortic diameter just proximal to the bifurcation, greatest small bowel wall diameter (using the thickest loop identified on scrolling through axial images), and volume of abdominopelvic fluid (within intraperitoneal and extraperitoneal compartments) for each patient using a previously described and validated semi-automated segmentation method [17–19]. Briefly, regions corresponding to confluent free fluid or blood on axial CT sections were selected by placement of seed points with subsequent 3D region growing into neighboring voxels with similar membership criteria. Overlapping regions were automatically merged. Following segmentation of all regions of confluent free fluid in the abdomen and pelvis, total volumes were automatically calculated and recorded in milliliters (mL) (Fig. 1).

Binary and categorical signs were assessed by the two more junior attendings (AW and DD), with disagreement arbitrated by a senior reader (UKB). These included the degree of mesenteric or body wall edema (graded as none, mild, moderate, or severe), presence of periportal edema, hydronephrosis, bilateral inguinal herniation (with fluid, bowel, or fat displacing or distorting inguinal canal contents) [20], and intra- or retroperitoneal fluid predominance. For multivariable logistic regression, laboratory and clinical values closest to the time of CT scan and most closely preceding decompressive laparotomy were abstracted from the electronic medical record including: bladder pressure, lactate and bicarbonate levels, pH, anion gap, and base deficit, based on previously described features of ACS [5, 6].

## Statistical analysis

Descriptive statistics of demographic and outcome variables are presented as mean ± SD (for normally distributed continuous data), median with interquartile range (for nonnormal data), and proportions (for binary data). Proportions between the two outcome categories were compared using the Fisher's exact test. Mean values were compared using the Mann–Whitney U test. Spearman's rho was used to assess correlation between continuous clinical and imaging variables. Multivariate logistic regression was used to determine independent predictors. Only those variables with significant differences between the two groups in univariate analysis were included in logistic regression. All tests were 2-sided, with the threshold of significance set at $p < 0.05$. Receiver

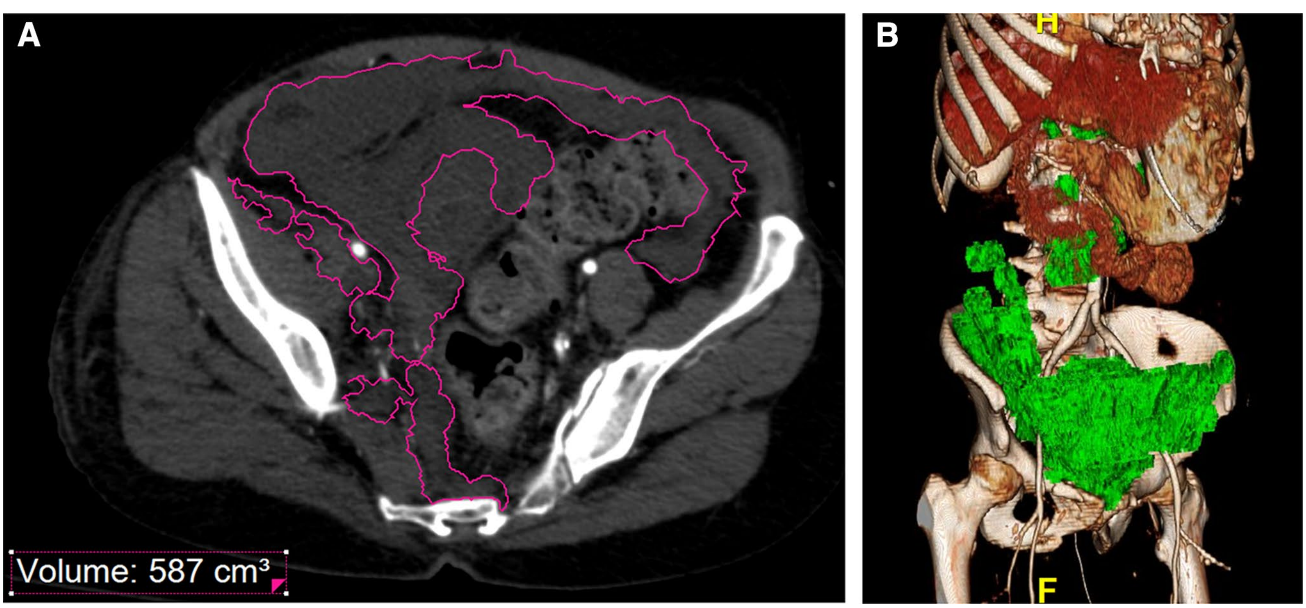


**Fig. 1** **a** 81-year-old woman pedestrian struck by motor vehicle, sustaining liver and spleen lacerations as well as pelvic fractures. Axial contrast-enhanced CT image following semi-automated free abdominopelvic fluid segmentation is shown, with a total volume of 587 mL. The seeded region growing technique forms sharp contours around free fluid and has previously been shown to be versatile for measuring multicompartmental, ill-defined, irregular, and laminar areas of fluid accumulation. **b** Same patient as **a**. Three-dimensional volume rendered image shows the entire segmented intra-abdominal fluid volume (green), partially obscured in the upper abdomen by contrast in the stomach and small bowel

operating characteristic (ROC) curve threshold analysis was used to determine optimal fluid volumes for predicting the need for early decompression at peak Youden index, sensitivity not falling below 90%, and specificity not falling below 90%. Area under the curve (AUC) was graded qualitatively as follows: AUC 0.5–0.6, fail; AUC 0.6–0.7, poor; AUC 0.7–0.8, fair; AUC 0.8–0.9, good; AUC 0.9–1, excellent [19]. Statistical analyses were performed using JMP 12.4 (SAS Institute, Cary, NC).

## Results

### Baseline characteristics

On average, patients were young (43.2 years), male (50/64), and sustained blunt traumatic injury (58/64) with discharge mortality of 54.7% (35/64). There was no significant difference in age, sex, injury severity score, or mechanism of injury between the early and late decompression groups (Table 1).

### Timing

Median times between both admission to decompression (early group: 0.48 days [IQR 0.29–1.0] versus late group: 5.5 days [IQR 2.8–7.7], $p=0.002$), and CT to decompression (early group: 0.23 days [IQR 0.08–0.6]) versus late group: 3.8 days ([IQR 2.1–6.3]; $p<0.0001$) were lower in the early decompression group than the late group with a high degree of significance and non-overlapping interquartile ranges, indicating the bimodal distribution of the early and late groups using a binary threshold of 24 h. Median time between admission and CT was brief and not significantly different between the early (0.16 days [IQR 0.03–0.41]) and late (0.09 days [IQR 0.03–2.4]) decompression group ($p=0.63$).

### CT, laboratory, and clinical features

Means for CT measurements and proportions of positive cases for binary variables were compared between the early and late decompressive laparotomy groups (Table 2). CT features that were significantly different in patients undergoing early decompressive laparotomy included increased mean abdominal fluid volume (Figs. 1 and 2; $p=0.001$), decreased mean IVC diameter (i.e., IVC flattening) ($p=0.009$), more severe mesenteric edema ($p=0.032$), and increased mean AP:T ratio ($p=0.009$). Proportions of patients with the presence of periportal edema ($p=0.77$), body wall edema ($p=0.36$), hydronephrosis ($p=0.31$), inguinal herniation ($p=0.56$), mean bowel wall diameter ($p=0.18$), mean aortic diameter ($p=0.41$), and intra- or retroperitoneal predominance of fluid ($p=0.82$) were not significantly different.

Mean bladder pressure measurements were only available in the electronic medical record in 19 of 64 patients. Mean bladder pressure measurements in the early decompression group were 28.8±7.5 mm water and in the late decompression group were 28.7±7.0 mm water, both consistent with grade IV intra-abdominal hypertension and ACS [1]. There was no significant difference in mean bladder pressure between the two groups ($p=0.76$; Table 2). Laboratory values at the time of DCL and CT were available for the vast majority of patients with the following proportions of patients at each timepoint: DCL (Lactate: 63 of 64, bicarbonate: 63 of 64, pH 63 of 64, base deficit: 63 of 64, anion gap: 54 of 64); CT (Lactate: 62 of 64, bicarbonate: 57 of 64, pH 57 of 64, base deficit: 57 of 64, anion gap: 62 of 64). Mean laboratory values at time of CT were significantly different in the early decompression group including: increased base deficit ($p=0.038$), decreased bicarbonate ($p=0.043$), and decreased pH ($p=0.024$). These values suggested a greater burden of clinical disease in the early decompression group.

### Multivariate analysis

Multivariate logistic regression was performed including imaging, clinical, and laboratory parameters to determine independent predictors of early surgical decompression after ACS. To avoid oversampling, only variables that were significantly different between groups in univariate analysis were incorporated as potentially explanatory variables. Multivariate logistic regression with backward elimination showed that abdominal fluid volume on CT ($p=0.012$, $\beta=0.002$—units of the regression coefficient are $\Delta$ in log odds of early decompressive laparotomy/mL; 95% CI 0.001–0.004) was the only independent predictor of early decompression, while the AP:T ratio, all other imaging markers, and all clinical and laboratory values were excluded as confounders. Correlation analysis revealed that abdominal fluid volume and time from CT to decompression were significantly inversely correlated ($\rho=-0.448$, $p=0.0002$).

ROC decision threshold analysis revealed volume thresholds for achieving sensitivity >90% and specificity >90% were 22 mL and 456 mL, respectively (Table 3). An intermediate threshold value of 133 mL was determined using the peak Youden index. The area under the receiver operating characteristic curve was 0.74 ("fair" range).

## Discussion

Refractory ACS requires decompressive laparotomy [1]. Several studies have demonstrated decreased mortality [7, 10], or improvement in cardiopulmonary and renal function

**Table 2** Clinical and imaging characteristics

| Covariate | Total Cohort $n=64$ | Early DCL $n=28$ | Late DCL $n=36$ | $p$ value |
|---|---|---|---|---|
| CT-DCL time (days) (median[IQR]) | 1.4 (0.3–4.5) | 0.23 (0.08–0.6) | 3.8 (2.1–6.3) | **< 0.0001** |
| Admit-DCL time (days) | 2.7 (0.5–6.4) | 0.48 (0.29–1.0) | 5.5 (2.8–7.7) | **0.002** |
| Admit-CT time (days) | 0.1 (0.03–1.4) | 0.16 (0.03–0.41) | 0.09 (0.03–2.4) | 0.63 |
| CT fluid volume (mL) (mean[SD]) | 338 (538) | 532 (681) | 185 (351) | **0.001** |
| AP:T ratio | 0.76 (0.15) | 0.82 (0.19) | 0.72 (0.07) | **0.009** |
| IVC diameter (mm) | 14.2 (6.7) | 11.7 (6.3) | 16.1 (6.5) | **0.009** |
| Aortic diameter (mm) | 13.3 (2.4) | 12.9 (2.2) | 13.6 (2.5) | 0.41 |
| Bowel wall diameter (mm) | 6.8 (3.8) | 8 (4.7) | 5.9 (2.6) | 0.18 |
| Mesenteric edema ($n$[%]) | | | | **0.032** |
| Mild | 23 (35.9) | 7 (25) | 16 (44.4) | |
| Moderate | 15 (23.4) | 11 (39.3) | 4 (11.1) | |
| Severe | 7 (10.9) | 4 (14.3) | 3 (8.3) | |
| Body wall edema | | | | 0.36 |
| Mild | 13 (20.3) | 8 (28.6) | 5 (13.9) | |
| Moderate | 14 (21.9) | 7 (25) | 7 (19.4) | |
| Severe | 7 (10.9) | 2 (7.1) | 5 (13.9) | |
| Periportal edema | 16 (25) | 6 (21.4) | 10 (27.8) | 0.77 |
| Hydronephrosis | 4 (6.3) | 3 (10.7) | 1 (2.8) | 0.31 |
| Inguinal herniation | 14 (22.2) | 7 (25.9) | 7 (19.4) | 0.56 |
| Location | | | | 0.82 |
| Intraperitoneal | 25 (41) | 9 (36) | 16 (44.4) | |
| Retroperitoneal | 26 (42.6) | 14 (56) | 12 (33.3) | |
| Bladder pressure (mm water) (mean[SD]) | 28.7 (7.5) | 28.8 (9.4) | 28.7 (7.0) | 0.76 |
| Bladder pressure measured ($n$[%]) | 19 (29.7) | 6 (21.4) | 13 (36.1) | 0.27 |
| Labs at CT (median[IQR]) | | | | |
| Lactate (mM) | 3 (2.2–6) | 3.3 (2.1–7.5) | 2.9 (2.2–4.4) | 0.71 |
| Bicarbonate (mEq) | 21 (18–23) | 18.5 (15.5–23) | 21 (19–24) | **0.043** |
| pH | 7.31 (7.2–7.4) | 7.24 (7.15–7.38) | 7.33 (7.23–7.41) | **0.024** |
| Base deficit | 4.9 (1.1–8.1) | 6.1 (3.8–12) | 4.6 (0.9–7) | **0.038** |
| Anion gap | 11 (7.8–14) | 11.5 (6.8–15) | 11 (8.3–13.8) | 0.79 |
| Labs at DCL | | | | |
| Lactate (mM) | 3.4 (2–5.7) | 3.7 (2.2–6.5) | 3.4 (1.8–5.7) | 0.36 |
| Bicarbonate (mEq) | 21 (18–24) | 20 (17–23) | 21 (18.3–24.8) | 0.33 |
| pH | 7.33 (7.2–7.4) | 7.22 (7.17–7.37) | 7.37 (7.24–7.41) | **0.015** |
| Base deficit | 4.7 (0.33–8.7) | 5.4 (1.9–10.8) | 3.1 (−0.2–7.2) | 0.12 |
| Anion gap | 10.5 (6.8–16.3) | 12 (8–17) | 10 (6–15) | 0.34 |

Bold values are statistically significant ($p < 0.05$)

*SD* Standard deviation, *IQR* interquartile range, *cm* centimeters, *mM* millimolar, *mL* milliliters, *mm* millimeters, *CT* computed tomography, *DCL* decompressive laparotomy, *AP:T* anteroposterior:transverse, *IVC* inferior vena cava

[21] with decompressive laparotomy within 24 h of development of ACS. A variety of binary, categorical, and semi-quantitative CT imaging features influence the decision to perform decompressive laparotomy within this time window in patients with refractory ACS to prevent fulminant organ failure and death [8, 11–13]; however, to our knowledge, abdominopelvic fluid volumes have never been evaluated as an objective actionable quantitative biomarker in this setting. In our population of trauma patients who ultimately developed clinical signs and symptoms of refractory ACS requiring surgical decompression, fluid volumes were the most significant univariate predictor of the decision to perform decompressive laparotomy within 24 h of the initial CT scan ($p = 0.001$), followed by the AP:T ratio and IVC flattening (both with $p$ value of 0.009). In multivariate logistic regression including both imaging features and relevant

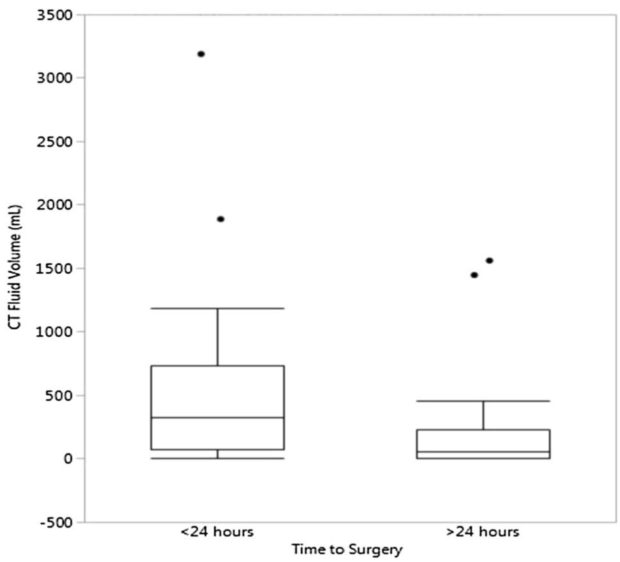


**Fig. 2** Box-whisker plots comparing fluid volumes in early and late groups, depict median (centerline), interquartile range (box), and 95% confidence intervals (whiskers). Mean abdominopelvic fluid volumes (mL) measured on preoperative CT were significantly higher in patients undergoing early (< 24 h) than late (> 24 h) DCL

laboratory and clinical values, abdominopelvic fluid volume was the only independent predictor. Higher CT fluid volume was also correlated with shorter times to decompression ($\rho = -0.448$, $p$=0.0002). ACS patients had 49, 122, and 232% increased odds of undergoing early decompression for 200 mL, 400 mL, and 600 mL increases in fluid volume identified on CT, respectively. In our ROC threshold analysis (Table 3), a volume threshold of 496 mL was likely the most clinically relevant, as it represents a specificity > 90% for identifying decision to treat refractory ACS within 24 h of CT. Laboratory values remain critical screening tools that flag initial suspicion of ACS, while bladder pressure measurements are an essential component of diagnosing and stratifying intra-abdominal hypertension and ACS. CT findings remain complementary.

We primarily assessed the feasibility of abdominopelvic volume measurements in a restricted cohort of patients that underwent decompressive laparotomy for refractory ACS. The primary limitation of our study is that our results are not readily translatable to the prospective clinical setting. However, our work shows that abdominopelvic fluid volume measurements are a granular and more predictive biomarker of the need for early decompression than previously described ACS-related CT features, which are coarse or subjective. The AP:T ratio may be considered a semi-quantitative precursor to objective quantification of abdominopelvic fluid volumes, and future studies assessing imaging signs of ACS using broader selection criteria should incorporate abdominopelvic fluid volume measurements as a predictor variable. Another limitation of our study was the under-reporting of bladder pressure measurements in the electronic medical record (EMR). We were only able to extract measurements in one-third of our cohort. Nevertheless, all of our patients had a documented diagnosis of refractory ACS requiring decompressive laparotomy. For those patients where bladder pressures were reported in the EMR, on the whole, measurements were severely elevated. Upon review of the electronic medical record, some patients without recorded bladder pressures were decompressed emergently, sometimes at bedside after clinical examination noting a markedly tense abdomen and had rapid evisceration under pressure at laparotomy with concurrent observed improvements in organ failure. When performed in a well-controlled manner, bladder pressure measurement is an essential indicator of the need for operative intervention [22–24]. Under-utilization of intra-vesical pressure monitoring in the emergent trauma setting has been noted by prominent practitioners in trauma surgery and critical care [8]; however, missing values in our study may have been largely related to incomplete data reporting in our new EMR. Our study focused primarily on comparing the utility of a newly described CT parameter with those previously described, and volumetric measurements are not implied as a tool to replace the standard of care at this time. In the future, improved automation of segmentation tasks using deep convolutional neural networks could facilitate the incorporation of this measurement into routine practice and promote consistent measurements that would facilitate comparison of results between research studies.

Other limitations include the relatively small sample size, and uncertainty in extrapolating the data beyond trauma patients. A recent systematic review [25] identified patients undergoing trauma laparotomy as the

**Table 3** Diagnostic accuracy of abdominopelvic fluid volume at different cutoff levels for predicting early surgical decompression

| Volume (mL) | TP | FN | FP | TN | Sensitivity | Specificity | Youden index |
|---|---|---|---|---|---|---|---|
| 21.7 | 26 | 2 | 20 | 16 | 0.93 | 0.45 | 0.37 |
| 133 | 20 | 8 | 12 | 24 | 0.71 | 0.67 | 0.38 |
| 456 | 11 | 17 | 3 | 33 | 0.39 | 0.92 | 0.31 |

*mL* Milliliter, *TP* true-positive findings, *FN* false-negative findings, *FP* false-positive findings, *TN* true-negative findings sub-population with the highest prevalence of ACS; however, ACS after trauma remains understudied.

## Conclusion

Overall, our results show that larger segmented abdominopelvic fluid volumes correspond more strongly with the decision to perform early surgical decompression in post-traumatic ACS than conventional CT imaging markers. Time effort and lack of widespread familiarity with semi-automated segmentation software remains a barrier to routine implementation.

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** IRB Approval: This study was approved by the University of Maryland Medical Center Institutional Review Board.

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