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REVIEW ARTICLE

Volumetric analysis at abdominal CT: oncologic and non-oncologic applications

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ABSTRACT

Volumetric analysis is an objective three-dimensional assessment of a lesion or organ that may more accurately depict the burden of complex objects compared to traditional linear size measurement. Small changes in linear size are amplified by corresponding changes in volume, which could have significant clinical implications. Though early methods of calculating volumes were time-consuming and laborious, multiple software platforms are now available with varying degrees of user-software interaction ranging from manual to fully automated. For the assessment of primary malignancy and metastatic disease, volumetric measurements have shown utility in the evaluation of disease burden prior to and following therapy in a variety of cancers. Additionally, volume can be useful in treatment planning prior to resection or locoregional therapies, particularly for hepatic tumours. The utility of CT volumetry in a wide spectrum of non-oncologic pathology has also been described. While clear advantages exist in certain applications, some data have shown that volume is not always the superior method of size assessment and the associated labor intensity may not be worthwhile. Further, lack of uniformity among software platforms is a challenge to widespread implementation. This review will discuss CT volumetry and its potential oncologic and non-oncologic applications in abdominal imaging, as well as advantages and limitations to this quantitative technique.

With advancements in medical imaging, greater emphasis is being placed on the potential use of quantitative imaging data in the research setting and in clinical practise. Continued growth in our understanding of the molecular groundwork of disease has been accompanied by a shift towards a more statistical approach to medicine and increasingly individualised methods of diagnosis and treatment. In support of this trend, the progression in imaging technology has resulted in the emergence of quantitative imaging data as a promising tool for use in both oncologic and non-oncologic disease. Quantitative imaging information supplements traditional qualitative radiologic assessment by providing a more robust evaluation that includes objective data, possibly serving as an imaging biomarker, or an indicator of a pathologic process or response to therapy.¹⁻³

As such, volumetric analysis of disease on CT has become increasingly relevant as a quantitative imaging technique, and the abundance of literature investigating and validating its use continues to rise. Multiple volumetric applications in abdominal imaging have been described, ranging from primary and metastatic abdominal cancer assessment to non-invasive staging of liver fibrosis, which will be highlighted in this article.

Not only is size an essential quantitative component to visual description, the size of a lesion on medical imaging can have significant implications on clinical decision-making and can modify the availability of certain therapies as treatment options. From both an intuitive and logical perspective, volumetric assessment is a more coherent depiction of an object's three-dimensional (3D) shape and size compared to uni- and bidimensional measurements. Complex, space-occupying lesions are challenging to accurately quantify with traditional linear measurements, which can be somewhat subjective and complicated by variability among radiologists. Furthermore, pathology is often not symmetric and can grow or decrease in size in a non-spherical fashion. With these concepts in mind, it seems logical that volumetric measures could be more useful for both initial lesion evaluation and for assessing change over time in some clinical scenarios. Volumetric measurements can be a more sensitive detector of growth because small changes in linear size are comparatively amplified in the corresponding volume change (Figure 1). This principle is demonstrated when considering the volume of a sphere ($V = 4/3 \pi r^3$) where an increase in the radius (r) corresponds to a much larger incremental change in volume. For example, if the radius increases from 4 to 5, the volume of a sphere

Figure 1. (a, b) Contrast-enhanced CT of the abdomen demonstrating volumetric measurement of a hepatic metastasis (red) 6 months apart (IntelliSpace Portal, Philips). (c) The table shows axial and volumetric measurements for the initial scan (bottom row) and the scan performed 6 months later (top row). The axial diameter of this lesion increased by ~10 mm (28%), but the volume increase by ~150%.

doubles ($5^3/4^3 = 125/64 \approx 2/1$). In this same manner, volumetric measurements allow for a greater margin of error and variability compared to linear measurements. An additional advantage is that volumetric analysis provides objective data that can be recorded and monitored over time or performed retrospectively.

As with any new or non-traditional imaging application, widespread use in clinical practise is often challenged by the feasibility of implementation into the routine workflow. In addition to accuracy, efficiency and reproducibility are determining factors for successful operation in the clinical setting. Earliest techniques for evaluating volume on CT involved multiplying the sum of individual transverse (axial) cross-sectional areas by the reconstruction interval,⁴ referred to as summation-of-area, which is time-consuming and labourious. Multiple software platforms are now available that offer manual, semi-automated, and fully automated methods for segmentation of an organ or lesion of interest and then interpolate that data to determine the volume. A typical manual technique requires hand tracing the region of interest (ROI) at the margin on every slice from the top to the bottom. Semi-automated methods involve less precise contour tracing around the lesion or organ on a single, few, or all image slices, and fully automated methods require no drawing or tracing. The software then detects the lesion margin using attenuation or edge-detection algorithms that are often proprietary to the vendor, and the user has the ability to make adjustments to the margins as needed. Semi- and fully automated methods are generally more efficient and equally accurate in measuring whole organ volumes,^{5,6} however, variable accuracy has been observed in smaller lesion

measurements.⁷ The accuracy and reproducibility of software-assisted segmentation and volumetric measurement of pulmonary nodules, however, has been well documented.^{8,9} Lung parenchyma surrounding a soft tissue nodule creates a high level of contrast, which is optimal for attenuation-based detection, and software algorithms can exploit this sharp boundary to accurately and consistently evaluate nodule volume. Measurement targets in the abdomen can be more challenging for both user and software segmentation, given that they are often closer in attenuation to surrounding structures and may be more irregular or infiltrating.

Volumetry software platforms include both commercially available packages, often as a component of a multitool image analysis suite, and open-source applications available for public use. The volume and complexity of cases and resource availability should be taken into consideration when implementing volumetric analysis into the routine clinical workflow. Lesion segmentation and adjustments can be performed on a dedicated standalone workstation by a radiologist, technologist, or other trained individual. A thin client with the software attached to the picture archiving and communication system (PACS) workstation allows for the user to access the data for manipulation and interpretation, eliminating the need for the user to move to a dedicated workstation. For clinical use, the software should ideally have the ability to electronically push a report or screenshot of the segmented organ or lesion with volumetric measurements into the PACS as a means for electronic documentation and comparison for future exams. Volumetric measurements can also be included in the text of the imaging report.

The lack of uniformity among software platforms remains a challenge to the widespread implementation of volumetric analysis. In a phantom study⁷ evaluating the accuracy and reproducibility of multiple readers using five software platforms, a liver phantom contained embedded lesions of varying size, attenuation, and shape to simulate both hyper- and hypovascular lesions. Significant variability was observed with volume measurements varying over twofold across vendors, and moderate intra- and interobserver variability was present. Even if efforts were made in clinical practise to use a single vendor for evaluating metastatic disease response, the authors concluded that variability in measurements unrelated to change in tumour size could still be a problem.

ONCOLOGIC APPLICATIONS

Imaging of cancer is a critical part of initial diagnosis, staging, and evaluating response to therapy, and the development of oncologic volumetry applications is an active area of research. Potential roles of volumetric analysis fall into three categories of applications: pretreatment tumour evaluation, tumour response to therapy (of both primary tumours and metastatic disease), and tumour therapy planning.

Pretreatment tumour evaluation

Volumetric analysis provides an objective estimate of the absolute bulk of tumour, which has been shown to have important implications on prognosis and risk of treatment failure for tumours outside of the abdomen, such as head and neck cancer, pleural mesothelioma, pulmonary adenocarcinoma, and Ewing sarcoma.^{10–16} In the abdomen, CT volumetry of some primary cancers has also shown potential use.

Endoscopy is an integral tool in oesophageal and gastric cancer diagnosis and staging, but some patients may not be conditioned to undergo such a procedure, and a malignant stricture may not allow for passage of the endoscope. Staging with CT volumetry may be useful in these cases. Hallinan et al¹⁷ retrospectively evaluated CT volumetry in staging gastric cancer in 153 patients and found excellent correlation between total tumour volume and T-stage, M-stage, peritoneal metastases, and final disease stage. Li et al¹⁸ found that gross tumour volume of gastroesophageal adenocarcinoma on CT correlated with regional lymph node metastasis and could be useful in differentiating grouped nodal stages. Nodal stage is important for patients who may undergo neoadjuvant chemoradiation to decrease N-stage prior to primary tumour resection and lymphadenectomy.¹⁸ Similar applications have been described with squamous cell oesophageal cancer.^{19,20} Li et al²⁰ evaluated 185 patients with squamous cell oesophageal cancer and found that primary gross tumour volume could better differentiate T-stage than the degree of circumferential involvement, tumour length, and maximum tumour thickness.

Tumour size is a well-established prognostic indicator for clear cell renal cell carcinoma (ccRCC).^{21,22} The question has been raised as to whether or not maximum tumour size accurately depicts tumour burden, and discrepancies between tumour volume and linear size have been described.²³ When evaluating

the potential impact of 3D size on prognosis, some series have suggested that increasing volume is associated with a greater risk of cancer-specific death in pT1 ccRCC.^{24,25} Jorns et al²⁴ retrospectively evaluated pathologic tumour volume of 955 pT1 patients after resection and found that volume was more highly associated with prognosis than tumour size in pT1a tumours, but not pT1b tumours. Song et al²⁵ reviewed tumour volumes on preoperative CT in 917 patients with pT1 ccRCC and noted different results when stratifying between stages pT1a/pT1b. In their study, tumour volume was associated with cancer-specific death in pT1b, but not pT1a. The authors proposed that the discrepancies could relate to differences in cohorts, tumour volumes, methods of volume measurement, and other factors. As such, the role of ccRCC tumour volume on prognosis shows potential, but needs further investigation.

Response to therapy

Evaluating tumour treatment response has become increasingly complex as novel, individualised treatment agents are more widely used. For patients receiving traditional cytotoxic chemotherapy, size remains a valuable metric for assessing treatment response, as these agents act by primarily killing neoplastic cells resulting in tumour shrinkage. The most widely applied and validated system in clinical trials for evaluating response in current use is Response Evaluation Criteria in Solid Tumours (RECIST) 1.1 which relies on the unidimensional or linear measures for overall tumour burden. World Health Organization (WHO) guidelines and the Southwest Oncology Group also support the use of one-dimensional (1D) and two-dimensional (2D) tumour measurements for evaluating response.²⁶ Though extensively adopted and applied, these guidelines assume all tumours are spherical and decrease uniformly in size.

Consequently, several theoretical advantages to volumetric analysis over linear measurements have been proposed. Volumetric analysis provides an objective measurement of overall tumour bulk, which has been useful in predicting treatment failure and prognosis of certain tumours.^{10–16} Growth in a non-uniform fashion and tumours with irregular contours that invaginate around normal structures may be better assessed with volumes that could actually compensate for the irregular tumour morphology. Further, volume measurements are more sensitive to small, but potentially clinically relevant unidimensional changes in size. For example, some studies have shown discordance between response criteria and volume measurements in the classification of tumour response assessment.^{27,28} While some have found that 3D or volumetric measures for tumour response appear to be the superior method,^{16,29–32} other authors have shown no difference in comparison to unidimensional measurements, and thus careful attention to the clinical scenario or application, as well as further validation and correlation with outcomes is needed to establish this resource-intensive measurement technique.

Response to therapy—primary tumour

Pre-operative radiation therapy and concomitant chemotherapy have been shown to downstage rectal cancer and, in turn, improve resectability. Groups have investigated the feasibility of

Figure 2. CTC 3D and 2D images (V3D Colon, Viatronix) (a, b) demonstrating a semi-annular adenocarcinoma (encircled) in the ascending colon. 2D, two-dimensional; 3D, three-dimensional; CTC, CT colonography.

volumetric analysis and the implications of volumetric tumour change. Dresen *et al*³³ retrospectively evaluated 67 patients who underwent MRI prior to and following chemoradiation and found that if the original tumour was $\leq 50 \text{ cm}^3$, a volume decrease of $\geq 75\%$ predicted that the tumour would be confined to the rectal wall at resection. Other groups found that a 70% or greater volumetric decrease was associated with downstaging^{34,35} and improved prognosis.³⁵ Rectal MRI has shown great utility in the pre-operative evaluation of rectal cancer, but volumetric analysis can also be performed on CT colonography (Figures 2 and 3). Luccichenti *et al*³⁶ evaluated feasibility of measuring total tumour volume compared to wall thickness of the primary rectal tumour in 15 patients. The authors established a volumetric threshold to mirror the concepts of WHO and RECIST guidelines, such that 65.7% decrease in the lesion diameter cubed was equivalent to the WHO and RECIST thresholds for partial response.

Figure 3. CT colonography (a) with a 3D rendering (V3D Colon, Viatronix) (b) showing a rectal cancer that is no longer visible at following up CTC (c, d) after chemotherapy and radiation. 3D, three-dimensional.

Earliest work on the potential significance of cervical cancer volume on CT patients undergoing radiation therapy found prognostic implications on 3 year local tumour control and 5-year survival.³⁷ On MRI evaluation of cervical cancer pre- and post-radiation therapy, Mayr et al³⁸ found that 70% of cervical tumours were not oval or round, and that most tumours decreased in a non-concentric fashion in response to therapy. The volume of tumour calculated by from orthogonal linear measurements was compared to tumour volume obtained by tracing an ROI around the margin. Measurements correlated well prior to and following radiation when the tumours typically had smooth margins or were small. Poor correlation of measurements was noted during therapy when tumour shape became complex, and the authors concluded that ROI-based volumetry may provide a better assessment of treatment response during radiation.

Response to therapy—viable tumour volume

Novel, molecularly targeted agents are problematic for size-based assessment of tumour follow-up because many of these agents are cytostatic and will act by halting tumour growth or cause tumour necrosis, rather than shrinking tumour size. Response to these therapies could stabilize or even increase tumour size, potentially misclassifying patients according to standard RECIST guidelines. Similarly, interventional locoregional therapies such as thermal ablation, transarterial chemoembolization (TACE), or Y⁹⁰ radioembolization may induce tumour necrosis, but the therapy effect on tumour size may be delayed (Figure 4). Further, these targeted therapies are non-systemic, often only addressing one or few lesions, and are not expected to prevent the development of additional tumours, thus potentially having inconsistencies with traditional response assessment criteria.^{26,39–41} This has led to the development of tumour viability-based criteria for specific cancers tailored to specific therapies, such as modified RECIST (mRECIST). Other viability-based criteria include the European Association for the Study of Liver (EASL) guidelines and Response Evaluation Criteria in Cancer of the Liver for hepatocellular carcinoma (HCC), Morphology, Attenuation, Size, and Structure criteria and Size and Attenuation CT criteria for RCC, and the Choi Criteria for gastrointestinal stromal tumour.^{42–47} These criteria incorporate other indicators for tumour viability, such as tumour enhancement on MRI or CT and FDG avidity in PET, but they also encounter the same obstacles as conventional anatomic biomarkers in terms of 1D and 2D quantification of viable tumour.

Volumetric assessment of tumour has continued to show potential utility when incorporated into viability-based criteria, but has primarily been investigated with MRI. For example, Tacher et al²⁹ evaluated an index lesion of HCC in 78 patients on MRI who underwent TACE and compared 1D and 2D response criteria (RECIST, mRECIST, and EASL) with 3D methods, volumetric RECIST (vRECIST) and quantitative EASL (qEASL). Cut-off values were selected to mirror those of the non-3D criteria, such that 65% decrease in overall tumour volume (vRECIST) or decrease in enhancing tumour (qEASL) constituted a response to therapy. Using these criteria, semi-automated 3D assessment of overall tumour volume and arterially enhancing tumour volume were better predictors of responders and overall survival. Sahu

et al³¹ evaluated whole liver enhancing tumour burden in 51 patients with bilobar neuroendocrine liver metastasis following TACE. Volumetric changes in whole liver burden identified survival difference between responders and non-responders and had excellent interreader agreement.

Following TACE, a greater amount of intratumoral lipiodised or ethiodised oil in HCC is associated with greater tumour necrosis and patient survival.^{48–50} A semi-automated technique for measuring the volume of deposited Ethiodol was evaluated by Monsky et al³² using segmentation software on unenhanced CT within 24 h after 37 TACE procedures in 27 patients with hepatic malignancies. The authors found good intra- and interobserver reproducibility in volumetric measurements of both Ethiodol deposition and tumour necrosis, as well as correlation with survival.

Response to therapy—metastatic disease

Prasad et al²⁸ evaluated 37 breast cancer patients with hepatic metastatic disease and compared 1D and 2D measurements with volume on CT. Volumetric assessment produced a discordant RECIST classification result from 1D criteria in 12 patients (32%) and a discordant WHO classification from 2D criteria in 13 patients. In a similar study, Mantatzis et al²⁷ evaluated 57 patients (17%) with hepatic metastases from colorectal cancer and also found discordance between RECIST unidimensional measurements and volumes. Lubner et al⁵¹ looked at 105 patients on cytotoxic chemotherapy with colorectal hepatic metastatic disease and found a similar rate of discordance (16%) in response classification. Of these discordances, 14/17 patients (82%) involved a change between partial response and stable disease, but survival was similar between these groups. Although there was discordance between volumes and unidimensional measures in this patient group, volumes did not appear to be a better predictor of survival in metastatic colorectal cancer.

Therapy planning

In patients with primary or metastatic liver tumours, the option of partial hepatic resection is reliant on the adequacy of the remaining liver remnant following surgery which has been shown to be an independent predictor of post-operative hepatic failure (Figure 5).⁵² Portal vein embolization of the non-remnant lobe causes diversion of portal blood flow and subsequent hypertrophy of the expected remnant, allowing patients who are initially deemed unresectable to be considered for resection.^{52,53} In pre-operative evaluation, CT volumetry can predict the future liver remnant (FLR) following resection and can also be used to evaluate for remnant hypertrophy following portal vein embolization (Figure 6). In healthy livers, an FLR volume of 20% is the recommended threshold prior to resection, but this threshold increases in the cases of exposure to hepatotoxic chemotherapy or cirrhosis, in which 30 and 40% FLRs are recommended, respectively.^{54–56}

Successful treatment of both primary and metastatic liver tumours with percutaneous thermal ablation requires knowledge of the required tumour-specific circumferential ablation margin to minimize the risk of local tumour progression.

Figure 4. Contrast-enhanced CT (a) and MRI (b) show an enhancing colorectal metastasis at the hepatic dome (white arrow), which is ^{18}F -FDG avid on PET/CT (c). The patient underwent transarterial radioembolization with Y-90 and follow up MRI at 1 month (d) and 4 months (e) after therapy show the lesion only slightly decreased in size (yellow arrow), but central necrosis and lack of residual enhancement are indicative of tumour response. FDG, fludeoxyglucose; PET, positron emission tomography.

Figure 5. CT volumetry performed for FLR volume in the evaluation for surgical resection of an intrahepatic cholangiocarcinoma. 3D images (Vitrea, Vital Images) (a) show the tumour (orange) and calculated tumour volume. Color overlays on contrast enhanced CT show exclusion of the mass (b) and the future liver remnant (c) during calculation. The liver remnant was 32%, but the patient had other comorbidities that precluded resection. 3D, three-dimensional; FLR, future liver remnant.

Volumetric analysis in ablation planning can be useful for ensuring adequate coverage of the ablation zone to encompass hepatic tumours and provide a margin for microsatellites of tumour in the surrounding liver parenchyma that are not apparent on anatomic imaging (Figure 7). Necessary ablation margins vary by tumour type and size, among other factors. For example, small HCCs (≤ 3 cm) generally require a 5 mm ablation margin, and hepatic metastatic disease requires a margin of 1 cm.^{57–59}

Figure 6. (a) Contrast-enhanced CT in a patient with metastatic colorectal metastasis (not included in these images) demonstrating segmentation of the FLR (pink), where the volume was initially too small for hepatic resection (13%) (IntelliSpace Portal, Philips). After undergoing portal vein embolization to the right lobe, compensatory hypertrophy of the left lobe increased the FLRV to 22% (b) and eventually to 49% (c). The patient successfully underwent extended right hepatectomy.

Figure 7. (a, b) During percutaneous microwave ablation, 3D rendering (NEUWAVE Ablation Confirmation Software, Ethicon) and non-contrast CT were obtained after placement of microwave ablation antennas (green, blue) into a HCC (red) in a cirrhotic liver demonstrating appropriate placement of the antennas bracketing the mass. (c, d) 3D and CT images with colour overlay show the ablation zone (delineated by the green circle) completely encompassing the lesion and providing an adequate circumferential margin. 3D, three-dimensional; HCC, hepatic cell carcinoma.

NON-ONCOLOGIC APPLICATIONS

A variety of applications for volumetric analysis in the abdomen exist outside of cancer imaging, which include the evaluation of colonic polyps, hepatic fibrosis staging, renal stone evaluation, and endoleak surveillance following endovascular repair of aortic aneurysms.

Colonic polyps

Volumetric growth on CT colonography (CTC) has been shown to be a useful biomarker in the assessment of colonic polyps and their clinical relevance.^{15,60,61} The risk of colonic neoplasia increases with polyp size, and immediate removal is recommended for polyps ≥ 10 mm, whereas diminutive polyps ≤ 5 mm are clinically insignificant and can be ignored. Small polyps measuring 6–9 mm are considered intermediate and current recommendations are for either 3-year interval CTC surveillance to evaluate for growth or immediate polypectomy at colonoscopy.⁶² Advanced adenomas show more rapid growth than non-advanced adenomas, and most other small polyps remain stable or regress⁶⁰ (Figure 8). For detection of growth, several studies have found that volumetric measurements are more reliable for assessment of interval change over time and can substantially amplify small incremental changes.^{60,61}

Liver fibrosis

In the pathway to cirrhosis, chronic hepatic parenchymal injury can cause a spectrum of fibrosis and result in a pattern of hepatic morphologic changes, which have long been described

Figure 8. 3D colon map (V3D Colon, Viatronix) from CT colonography (a) showing the location of a sigmoid polyp (arrow, red dot), which measured 7.8 mm at initial screening (b). Polyp segmentation for volume measurement is shown on both the 3D and 2D (inset) views. Follow-up CT colonography 1 year later (c) shows that the polyp grew only 0.8 mm, but showed a 50% increase in volume (to 205 cm³). At same-day colonoscopy (inset), this lesion was removed and proven to be an advanced (tubulovillous) adenoma. 3D colon map (d) showing the location of three small polyps in the right colon (arrows, red dots). 3D images of the proximal transverse colon polyp initially (e) and at surveillance screening 16 months later (f) show an increase from 6.0 to 8.0 mm and increase in volume by 203%. Similar growth was seen with the cecal polyps. Once removed, the proximal transverse colon polyp was a tubular adenoma (non-advanced), and the two cecal polyps were advanced (tubulovillous adenomas). Reprinted, with permission, from reference.⁶⁰ 2D, two-dimensional; 3D, three-dimensional.

on cross-sectional imaging.⁶³ Atrophy of the Couinaud segments IV through VIII (the left medial segment and the right hepatic lobe) is usually accompanied by compensatory hypertrophy of segments I through III (the caudate and the left lateral segment). Prior to reaching irreversible cirrhosis, earlier stages of hepatic fibrosis may be reversible. Liver biopsy can provide fibrotic staging, but is invasive, expensive, and prone to sampling error.⁶⁴ As a non-invasive approach for liver fibrosis staging, a volumetric ratio comparing the hypertrophied segments (I–III) to the atrophied segments (IV–VIII), or the liver segmental volume ratio (LSVR), has been described (Figure 9).^{65,66} By isolating segments I–III and IV–VIII on cross-sectional imaging and then measuring separate volumes of each component, the ratio of the hypertrophied segment volume to the atrophied segment volume represents the LSVR. This ratio can quantify and accentuate hepatic morphologic changes, which can be somewhat subjective and subtle in early stages of the fibrotic spectrum. Using CT segmentation software, Hunt *et al*⁶⁵ found that the combination of LSVR and splenic volume was superior to other previously described non-invasive measures (including total liver volume and caudate-to-right lobe ratio^{67–69}) in differentiating normal and

Figure 9. Examples of normal and cirrhotic liver morphology on 3D (Liver Analysis application, IntelliSpace Portal, Philips) (a, d) and contrast enhanced CT (b, e) with segmentation color overlays (c, f) where segments I–III are yellow and segments IV–VIII are green. Normal relationship between segments are seen in the normal liver (a–c). The bottom row (d–f) demonstrates atrophy of segments IV–VIII and hypertrophy of segments I–III. (e) Note the marked hypertrophy of segment I (arrowheads). Reprinted, with permission, from reference.⁶⁵ 3D, three-dimensional.

cirrhotic livers, and there was excellent agreement of between readers of varying experience level. Pickhardt *et al*⁶⁶ compared volumetric measures with the pathological METAVIR staging of fibrosis in 624 patients who underwent liver biopsy within 1 year of the CT used for volume analysis. The authors found that in normal subjects (F0), the mean LSVR was 0.26 and the mean splenic volume was 215.1 cm³. In cirrhotic subjects (F4), the mean LSVR was 0.56 and the mean splenic volume was 790.7 cm³. LSVR showed progressive differentiation among the pre-cirrhotic stages of fibrosis (F1–F3). When LSVR was combined with splenic volume, this combined metric was accurate in discriminating significant ($\geq F2$) and advanced ($\geq F3$) fibrosis. Hepatosplenic volumes on CT could serve as a useful biomarker for staging and, like other applications of volumetry, can be applied retrospectively or prospectively.

Renal stones:

CT volumetry has been used for the assessment of renal stone growth (Figure 10). Because obtaining accurate and reproducible linear measurements can be challenging in stones with complex 3D shapes, some groups have shown that volumetric automated analysis provides a more accurate and reproducible assessment of stones when compared to manual linear measurements.^{70–72} Similar to the utility of measuring volumes in colon polyp surveillance, small incremental changes in linear stone size are more likely to be detected because changes in volume are comparatively amplified. Furthermore, stone volumetry may provide a metric with greater clinical implication than other radiographic measures. Selby *et al*⁷³ found that automated total stone volume was more predictive of symptomatic stone events on multivariate analysis, independent of other imaging metrics, such as stone size and number.

Figure 10. Unenhanced CT (a-c) and corresponding 3D images (Ziosoft) (d-f) illustrate the asymmetric growth of a renal stone over 10 months. The linear stone diameter doubled (6.8 to 14.8 mm) between (a) and (b), and the corresponding volume of the stone increased by about 600% (49.6 to 200.3 mm³). (c) The stone continued to grow with a 39% increase in linear size (14.8 to 20.7 mm) and a 173% increase in volume (200.3 to 547.6 mm³). Reprinted with permission from reference.⁷⁰ 3D, three-dimensional.

Endoleak surveillance

Following endovascular aneurysm repair, CT volumetric assessment of the abdominal aortic aneurysm sac is helpful in the evaluation for endoleak. Endovascular stent repair of an abdominal aortic aneurysm excludes the aneurysm sac from high-pressure blood flow to prevent rupture. Thus, persistent blood flow within the sac will cause an increase in size of the excluded sac and is an indicator of a significant endoleak.^{74–78} In a study of 63 endovascular aneurysm repair patients, 19 patients had endoleaks, and aneurysm sac volume was a better indicator of early endoleak compared to maximum transverse diameter of the sac. Further highlighting the unreliability of sac diameters, decreasing aneurysm diameters were seen in 37% of patients with increasing sac volumes.⁷⁴ Bley et al⁷⁵ described an unenhanced CT algorithm using volumetric aneurysmal sac measurement, thus decreasing radiation dose and sparing patients with renal dysfunction from exposure to iodinated contrast material. The authors concluded that endoleak surveillance could be sufficiently assessed without

Figure 11. (a, b) 3D image (Advantage Workstation, GE Healthcare) and contrast enhanced CT of the abdomen demonstrate an infrarenal abdominal aortic aneurysm. (c-e) Follow endograft repair, 3D images obtained from unenhanced CT show an expected decrease in the volume of the aneurysm sac over time (231 to 173 cm³), excluding the presence of an endoleak and therefore i.v. contrast was not needed. 3D, three-dimensional.

i.v. contrast unless the volume of the aneurysm sac increased more than 2%⁷⁵ (Figure 11).

CONCLUSION

CT volumetry has shown to be useful in a large spectrum of both oncologic and non-oncologic applications, and a number of advantages to volumetric analysis exist that substantiate its use in certain roles. Data establishing clinical efficacy, however, are limited, but continued research efforts in the quest for imaging biomarkers may bring further validation. Several technical challenges and limitations of this technique, including non-standardisation among and within software platforms as well as varying degrees of automation and labour intensity, will also need to be resolved before widespread clinical implementation.

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