CT Dynamics: The Shift from Morphology to Function

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Abstract CT has historically been a static imaging modality, but the human body is in constant motion. The need to visualize the underlying physiology has driven CT to capture functional information as well. CT dynamics can be acquired using several different acquisition techniques on both conventional and high-end scanners. Dynamic joints, dynamic CTA, perfusion, and dynamic lungs are all emerging applications of CT dynamics. The use of dynamic CT can yield key diagnostic information not available from static scans.

Keywords Computed tomography ·
Dynamic volume CT · Dual source CT ·
320-row CT · Dynamic imaging

Introduction

Since its beginnings as solely a neurological imaging device, the number of applications of CT imaging has expanded tremendously. Currently, CT has applications for every anatomical region and nearly every physiological process. CT technology has seen both gradual improvements and breakthrough advances driven by accuracy and sensitivity as well as in speed and economic efficiency. The use of CT has steadily increased by more than threefold since 1993 to over 70 million scans per year [1]. By and large, however, CT has traditionally been used as a

modality that produces static images of morphology with high spatial resolution and good soft tissue contrast.

Static anatomic information has always been used to infer the underlying physiology and function. One good example of this is in coronary angiography where the physiologic significance of a lesion is determined wholly by its degree of stenosis: a morphologic metric. However, landmark clinical trials such as COURAGE [2] and the FAME I [3] and FAME II [4••] trials have shown that such metrics are inadequate. COURAGE showed that the outcome of patients receiving percutaneous coronary intervention (PCI) driven solely by anatomical measures was no better than for patients who received no surgical intervention but were treated with optimal medical therapy (OMT). Subsequently, the FAME trials showed that using fractional flow reserve (FFR), a functional metric, to drive PCI led to a significant reduction in hospitalization and urgent revascularization compared to the OMT group. In order to realize this kind of higher precision imaging, earlier diagnosis, and direct impacts on patient therapy, there is currently a shift in the nature of CT applications from morphology to function. This shift in CT clinical applications towards the imaging of function has opened up a new paradigm in clinical imaging: CT dynamics.

The human body is an inherently dynamic machine. Whether examining the flow of blood through the vessels and perfusing into tissue, the expansion and contraction of the lungs, the movement of the vocal cords, or the flexion and extension of the wrist, the body is in constant motion. The clinical ability to capture that motion and monitor the anatomic and physiologic changes over time can add significant information to the diagnostic process. Dynamic joint instabilities, myocardial wall motion abnormalities, and blood flow measurements all require the imaging of volumetric anatomy over time.

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Acquisition

The idea of dynamically acquired CT data is not new. In fact, two unconventional CT designs, the Dynamic Spatial Reconstructor [5] (DSR) and the Imatron electron beam scanner [6, 7] were both built in the 1980s primarily as dynamic scanners focused on cardiac imaging (Fig. 1). The DSR consisted of 28 x-ray tubes mounted in a semi-circle with opposing image intensifiers and video cameras. The system could image with z-axis coverage of 24 cm with a 38 cm x–y field of view. The machine rotated continuously and could trade off temporal and spatial resolution. With 28 views, it could produce 60 frames per second or use all 240 views that could be acquired in a 2 s acquisition. While this machine had limitations with regards to cost and practicality for widespread clinical deployment, it was a pioneer in dynamic imaging. Similarly unique in design, Imatron's electron beam scanner departed from the conventional design of an x-ray tube and substituted in its place an electron beam being swept across a large semicircular tungsten target array. The electron-beam sweep provided the opportunity to produce a partial-scan temporal resolution as fast as 50 ms. Furthermore, the Imatron system was the first volume CT system covering 8 cm of anatomy with no table motion. There were two detector-rows and four sets of tungsten targets for the beam to sweep over. In all, this allowed eight distinct 8 mm slices in the z-direction through the anatomy. By cycling through the four sets of targets repeatedly, the system was able to capture a volume of anatomy dynamically leading to the scanner's nickname: cine CT. While these early designs for dynamic CT did not ultimately persist, they did pioneer CT dynamic imaging which is currently experiencing a clinical resurgence.

Modern, commercially-available CT scanners offer several methods for acquiring dynamic CT data: low pitch helical, helical shuttle, and dynamic volume imaging. Each acquisition method provides certain advantages and limitations in the collection of data.

Low-Pitch Helical

One of the simplest ways to acquire dynamic data with a conventional helical scanner, the low-pitch helical approach can be employed for any anatomy where the motion is periodic and the anatomy returns to the same spatial position each cycle. By moving the table slowly enough to capture the same anatomy throughout its cyclical motion, it is possible to re-sort the projections from multiple different detector rows to reconstruct a given section of anatomy at any arbitrary time point in its cycle. Early work with this approach focused solely on imaging the

coronary arteries [8–11], while more recent studies have used this approach with respiratory gating in the lungs [12].

The main advantage of low-pitch helical scanning is that it can be used on any multidetector row helical scanner. The technical requirements fall on the reconstruction algorithm, however, and there is a significant tradeoff in radiation dose since the technique relies on selecting the relevant projections from an overabundance of data. Also, when the assumption of periodicity is broken, the reconstructed images can contain blurring and artifacts.

Helical Shuttle

With the helical shuttle technique, the same section of anatomy is scanned periodically with a helical acquisition, typically back and forth through the anatomy [13]. With this type of acquisition, large sections of anatomy can be captured over time. The trade-off, however, is that the volumetric temporal resolution is poor, degrading as the scan distance increases. Therefore, it is not possible to capture the rapid motion of the heart, lungs, or joints with this technique. Recently however, some groups have used this technique to capture multiple phases of vascular contrast flow [14]. It is worth noting that with this technique the absolute phase of motion varies along the length of the acquisition. That is, the difference between the temporal phase at the start of the imaging volume and the end increases with increasing scan distance.

Dynamic Volume

The most direct way to measure dynamic motion, especially of rapidly moving anatomy, is by repeated scanning without table motion. This can be accomplished with any modern CT scanner, although the technique is limited by the craniocaudal or z-axis coverage of the system. For example, most 64-row systems can cover approximately 4 cm of anatomy dynamically. Other systems have greater anatomic coverage with 8 and even 16 cm of anatomy being acquired in a single rotation without table motion [15, 16]. The volume scan mode allows the imaged volumes to be interrogated dynamically with temporal uniformity, i.e., the entire volume is imaged at the same temporal phase [17]. The trade-offs with the wider volume systems are an increase in scatter at the detector and the necessity of image reconstruction to handle the cone beam acquisition geometry.

Clinical Applications of Dynamic CT

With these acquisition modes, CT has now become a robust modality for the visualization of the human body in

Fig. 1 Early pioneers of dynamic imaging with CT. **a** The Dynamic Spatial Reconstructor (DSR) was built from 28 x-ray tubes and image intensifiers. **b** Imatron's electron beam scanner swept an electron

beam across a large, semicircular tungsten target surrounding the patient. Figures reprinted with permission

motion. A number of new clinical applications have arisen with the increasing use of dynamic CT: musculoskeletal kinematics (MSK), dynamic CTA, CT perfusion, and other exams with anatomic motion. With each application, the dynamic nature of CT plays an important role. Some applications, like MSK, require high volumetric temporal sampling, while others, like perfusion, may be adaptable to lower sampling rates.

MSK Kinematics

Joint imaging in radiology has historically focused on morphology rather than function by acquiring static images of a stationary joint. When there is an obvious deformity in the joint, this approach can be useful. However, this is often not the case, as with joint instabilities [18], where the diagnosis relies on interrogation of the joint in motion

(Fig. 2). While there are some other non-invasive dynamic techniques available such as fluoroscopy [19] and ultrasound [20], only CT provides 4D imaging with high temporal and spatial resolution. It is possible to image a series of static positions with helical CT; however, a fluoroscopic study of the carpal bones has shown that there can be sudden changes in position which would be missed using a “stop-motion” technique [21].

While the earliest work in CT imaging of joint mechanics was conducted by Stanford et al. and Shapeero et al. [22, 23] on the electron beam scanner, early MDCT feasibility work by Tay et al. [24, 25] employed a cadaveric wrist attached to a periodic motion device and scanned with a low helical pitch and retrospective gating. While this work showed the potential of the imaging of joint motion with CT, later work by members of the same group concluded that the imperfect periodicity inherent in patient imaging produces banding artifacts with the retrospective technique [26]. In this subsequent work, this team examined dynamic imaging of the cadaveric wrist without table motion. They showed that the dynamic imaging did not rely on periodic motion and eliminated the banding artifacts. While the longitudinal coverage for this study was only 38.4 mm, Leng et al. found this to be sufficient for evaluation of scapholunate instability where the main focus is on the proximal carpal bones.

Kalia et al. [27•] first reported on the technical feasibility of dynamic joint imaging with a wide detector CT scanner. Using a 256 detector-row prototype system with 12.8 cm of longitudinal coverage, they dynamically evaluated both the knee and the wrist in vivo. Three volunteers underwent bilateral knee imaging for patellofemoral evaluation and three others underwent bilateral wrist imaging for both supination-pronation and radioulnar deviation. The investigators found that the image quality was rated as “good” in all cases with some artifacts noted. Furthermore, the ability to depict normal joint motion was rated with the highest rating of “well depicted” for all joints examined. They concluded that the wide-detector dynamic evaluation of dynamic joints was feasible and showed good potential for evaluation of pathomechanics including patellofemoral maltracking, carpal instability, and chronic distal radioulnar joint instability. This work was followed up using a 320 detector-row system with 16 cm of longitudinal coverage by Halpenny et al. [28] looking specifically at scapholunate instability in a patient. They demonstrated the ability to measure the increase in the scapholunate distance during the motion that caused the patient the most pain.

Recently, Wassilew et al. [29] looked at the dynamic assessment of femoroacetabular impingement and subluxation in 30 patients using the 320 detector-row scanner. They compared the results with intraoperative findings and found that the dynamic CT had a high degree of accuracy

and was a new option for visualizing morphology and impingement prior to surgery. The main limitation of this approach was noted to be its increased radiation dose over static, diagnostic CT of the same region.

Dynamic CTA

CTA has been shown to be a useful technique in the detection and evaluation of morphological pathologies such as vessel stenoses, aneurysms, congenital abnormalities, and arteriovenous malformations (AVM). However, with static images, it is impossible to demonstrate the dynamic properties of these pathologies such as early venous filling and the feeding and draining patterns of an AVM [30]. Further, while static CTA has been shown to be a sensitive and specific test in the detection of endoleaks [31], invasive digital subtraction angiography (DSA) remains the gold standard in their classification as well as in the characterization of flow patterns in aneurysms and AVMs. While there are several modalities that can measure flow in the vessels such as DSA, ultrasound, and dynamic MR, dynamic CTA (or 4D-CTA) investigation of these pathologies (Fig. 3) offers a non-invasive alternative to DSA, is more widely available than MR, and can access more vessels than ultrasound.

Bent et al. [32•] were the first to report on volumetric dynamic CTA evaluating its utility in the characterization of endoleaks following fenestrated endovascular aortic aneurysm repair (f-EVAR). The report argues that while DSA is the gold standard in these cases, it is a challenging procedure due to the high number of arterial puncture sites and contrast injections, as well as carrying a high radiation dose. The group used a 320-detector row system, scanning dynamically and continuously for 18 s with a 0.5 s rotation time. They were able to clearly demonstrate a type III endoleak in their patient and argued that such a demonstration would not be possible with a static CTA exam.

Brouwer et al. [33] described dynamic CTA evaluation of shunting lesions such as AVMs and DAVFs using the 320-detector row scanner. They generated 22 time points from the CT data for each case, and used the initial time point as the subtraction mask. The resulting data were compared to standard catheter angiography (CA) in the same patients. They showed comparable diagnostic ability between CA and dynamic CTA for these cases demonstrating early venous filling, cortical venous reflux, and a benign DAVF. Simultaneous visualization of all cranial vascular territories was noted using CT compared to the selective vessel injections possible with CA. An advantage of CT is that it allows the visualization of the anatomy and function from any angle in post-processing where CA views must be determined during the procedure. The maximum

Fig. 2 Dynamically acquired musculoskeletal imaging of the wrist showing increased scapholunate distance. Data were acquired in dynamic volume mode with 16 cm of coverage. Images courtesy of Dr Alain Blum

radiation dose for CT was reported to be 5.1 mSv. In a follow-up study, Willems et al. [34] demonstrated high correlation between dynamic CTA and CA in the detection of arteriovenous malformations of the brain in a small cohort of 17 patients. They found the main limitations of 4D-CTA were in the accurate estimation and identification of some of the angioarchitectural details such as underestimation of the nidus size and misinterpretation of indirect feeding through pial collaterals. Ultimately, they found 4D-CTA to be sufficient to accurately diagnose and classify the shunt. In a separate study, Willems et al. [35] also describe the ability of 4D-CTA to identify and classify DAVFs in a cohort of 11 patients. They found the technique to be robust unless the patient had a small, slow-flow DAVF in which case the pathology might be missed. Finally, Krings et al. [36] reported on the flow dynamics of an intracavernous aneurysm and evaluate the aneurysm's pulsatility using

dynamic CT. They postulated that the focal pulsations were associated with the subsequent growth of the aneurysm in the region that showed pulsatility.

Recently, Meinel et al. [37] reported on time-resolved angiography using a dual-source scanner in a multi-phase helical shuttle exam using a technique previously described by Sommer [38•]. In this study, they scanned 14 patients with known or suspected aortic dissection using six reconstructed time phases covering 48 cm. The time between each phase was 6 s. They demonstrated the difference in enhancement time between the true and false lumen and the oscillation of the dissection membrane, difficult to visualize without dynamics. The average radiation dose was 27.7 mSv. Sommer et al. [39] used a similar scanning technique to detect and classify endoleaks compared to contrast enhanced ultrasound. In a cohort of 54 patients, they acquired 12 helical phases of 27 cm with 2.5 s between

Fig. 3 Dynamic subtraction CT angiography of the whole brain. *Dataset* shows timing of dynamic vessel filling in 4D. Data were acquired in dynamic volume mode with 16 cm of coverage. Images courtesy of Toshiba Medical Systems Corporation

each phase. They showed high sensitivity and specificity for detecting and classifying primarily type I and type II endoleaks with an average radiation dose of 14.6 mSv. In a similar study, Lehmkuhl et al. examined the rate of type I and type II endoleak detection with no reference standard using, rather, a metric of diagnostic confidence. They found that endoleaks were more likely to be found in the dynamic scan which contained phases that were not typically acquired in a standard biphasic CTA exam.

Barfett et al. [40] used dynamic volume CT in a phantom to show the feasibility of measuring blood flow directly. Using a method from conventional angiography [41], the group compared the bolus profiles at two locations within a cadaveric vessel. They noted that the dynamic CT

technique holds advantages over both Doppler ultrasound and phase contrast MRI in that it is rapid, user independent, and can potentially measure the flow in small vessels that are inaccessible to ultrasound. However, this technique is limited by the need for a reasonable distance between the bolus measurements to correspond to the precision of the temporal measurements, as well as by the sensitivity to different phases of the cardiac cycle.

Perfusion

Distinct from the imaging of morphological motion and vascular dynamics, perfusion imaging attempts to quantify

the capillary flow within the parenchyma of various organs in the body. First described by Axel [42], perfusion imaging is typically accomplished in CT by analyzing the enhancement of the tissue over time as iodinated contrast washes in and out of the tissue. The plot of this enhancement over time is known as a time-density curve (TDC), and by repeated imaging of the anatomy of interest, the TDC can be sampled and flow quantified. Early CT perfusion work was pioneered on the electron beam scanner imaging the myocardium [43, 44]. More recently, CT neuroperfusion has become an invaluable application for the triage of patients with suspected stroke [45–48] (Fig. 4). CT is fast, inexpensive, and widely available, making it a viable option for stroke workup. The typical exam consists of an unenhanced acquisition to rule out hemorrhage, a CTA exam from the aortic arch to the vertex of the skull to map the head and neck vasculature, and a dynamic CT perfusion (CTP) exam to determine the level of ischemia and infarction in the brain [49]. In order to cover the entire anterior circulation territory or, better yet, the entire brain, 8–16 cm of z-axis coverage is required. This can either be accomplished with a wide volume detector scanner [50–52] or by using jog [53] or helical shuttle [54] modes of acquisition.

Currently, CTP is being used in nearly every organ of the body (Fig. 5). Liver perfusion with CT can help assess chronic liver diseases such as chronic hepatitis, liver fibrosis, and cirrhosis as well as detect primary hepatic carcinomas [55, 56]. Other recent studies have looked at reproducibility [57], assessing and lowering the radiation dose [58, 59], comparing to arterial spin labeling with MR [60], and have examined different analysis methods [61]. Miles et al. [62] first described the use of perfusion CT in the pancreas in 1995, but widespread application of the technique has been limited by the inability of conventional CT to cover the entire organ and the respiratory motion that can shift the organ out of the field of view. More recently, Kandel et al. [63] described the use of dynamic volume CT in the pancreas (Fig. 6) to overcome these limitations. Similarly, others have described dynamic perfusion of the pancreas using 4 cm of coverage [64–66]. Furthermore, there are numerous reports of the utility of perfusion [67] in the lung [68, 69–71], kidney [72–74], spleen [75, 76], and colon [77–79]. Finally, there is a great deal of work ongoing for both dynamic [80, 81] and single-shot [82–84] myocardial perfusion.

Dynamic Airways and Lungs

While static CT has a large number of applications in the lungs and airways, the dynamic motion of this anatomy has historically been inferred from one or more scans [85].

While earlier studies by Lee et al. [86] looked at tracheomalacia during forced expiration with a static helical scan, Wagnetz et al. [87] did a similar study with dynamically acquired volume CT in six patients with a suspicion of tracheomalacia. They imaged for either 4.5 or 6.5 s from the end of inspiration through the forceful expiration phase. By scanning dynamically, they found that the peak airway collapse did not occur synchronously; rather, the distal trachea had peak collapse at 2–3 s into expiration where the proximal trachea showed peak collapse at 3–4 s. They reported a maximum radiation dose of 8.2 mSv for this study. In another airway study, Low et al. [88] examined abnormal laryngeal function in patients with difficult to treat asthma. They imaged the larynx dynamically during normal breathing over the course of 1 respiratory cycle. They found abnormal narrowing in the vocal cords in 50 % of the asthmatic patients compared to a cohort of healthy volunteers. The maximum dose for the dynamic study was reported to be 2 mSv.

Several reports have described the dynamic visualization (Fig. 7) of respiration in the lungs [89–91]. Some approaches use a step-and-shoot acquisition covering small volumes at a time and using an external marker to achieve respiratory gating [92]. Others use a low helical pitch, typically around 0.1, to retrospectively gate the lungs during a helical scan. Greenberg [93] describes the use of wide detector scanning to image the pediatric lung. He found that the dynamic acquisitions often added diagnostic information that was unavailable from static scans, including a better appreciation for tracheo- and bronchomalacia and a more accurate assessment of air trapping. He reported a mean radiation dose of 1.7 mSv in the cohort of 24 infants and small children.

Conclusion

Nearly any anatomy in motion can be imaged with dynamic CT. There is increased diagnostic information available over and above static imaging by repeatedly interrogating the anatomy during motion. Through the use of dynamic axial, low-pitch helical, shuttle mode, or wide volume scanning, anatomic dynamics can be captured and visualized with most modern CT systems. There are, however, a few caveats and limitations to the employment of these dynamic acquisitions.

One challenge is the radiation dose associated with repeated scanning of the same anatomy. Since dose is cumulative, every imaging phase multiplies the amount of energy absorbed by the patient. This is typically mitigated by using scan techniques that result in static images that are noisy and of lower quality than the standard diagnostic technique. With contrast enhanced studies, the use of a

Fig. 4 Dynamically acquired brain perfusion exam showing core infarct and penumbral region in the left hemisphere. Individual maps show **a** blood flow, **b** blood volume, **c** mean transit time, and **d** tissue characterization. Images courtesy of GE Healthcare

Fig. 5 Quantitative perfusion maps of a 76 year old man with renal cell carcinoma. Shown are coronal views of the temporal maximum projection, blood flow, blood volume and flow-extraction product.

Data were acquired in periodic spiral mode with 10 cm coverage. Parameter maps were calculated using a model based deconvolution technique [73]. Images courtesy of Siemens Medical Solutions

Fig. 6 Dynamic volume pancreatic perfusion showing **a** a well defined 1.4 cm mass in the pancreatic head (*arrow*) with upstream ductal dilatation is shown in this curved reconstruction. Low blood flow within the lesion **b** with values around 0.56 ml^{-1} . Whipple

procedure was performed and pathology confirmed a pancreatic adenocarcinoma. Data were acquired in dynamic volume mode with 16 cm of coverage. Images courtesy of Patrik Rogalla

Fig. 7 Dynamically acquired demonstration of tracheomalacia at **a** full inspiratory phase showing normally expanded trachea and bronchial tree, **b** during forced expiration showing collapse of the posterior wall of the left bronchus and trachea, and **c** at full expiration with severe collapse of the trachea and total collapse of the bronchi. Data were acquired in dynamic volume mode with 16 cm of coverage. Images courtesy of Narinder Paul

lower tube potential, typically 80 or 100 kV, can also lower the dose [94]. Furthermore, with the increase in iterative reconstruction and time-domain filtering techniques [95], the image quality of the reduced dose dynamic acquisitions can be greatly improved. Finally, as with all imaging, there are specific indications that benefit from a dynamic scan and others that do not, so care should be taken to use dynamic CT where it is most warranted.

There are even a few challenges inherent in the physiology and kinesiology of the body. For example, the field of dynamic MSK diagnostics is an emerging clinical field and the understanding about what “normal” motion is and what its boundaries are may not be completely known. Furthermore, many MSK pathologies are exacerbated by or only manifest under weight-bearing conditions. Simulating this can be difficult in most CT scanners, although one dedicated design has been proposed [96]. Similarly, for myocardial perfusion imaging, pharmacological stress

agents must be employed to image the heart during hyperemia. Creating or simulating these situations can add to the challenge of dynamic imaging with CT.

Another challenge with dynamic CT is the sheer volume of image data that is generated by these techniques. A 20 phase perfusion scan with 320 images per volume is over 6000 images. Therefore, the PACS systems, analysis packages, and infrastructure need to be prepared to handle larger volumes of data when dynamic scanning is involved. Furthermore, the software used to create these 4D images must reflect this new way of looking at form and function, and produce intuitive ways of managing and presenting this data to the reading clinician.

Ultimately, when used for the proper clinical indications, dynamic CT can be a useful and robust part of a diagnostic algorithm. Minimizing acquisition technique, reducing kV where appropriate, and employing iterative reconstruction and time-domain filtering provides a strong

foundation for routine dynamic imaging. Furthermore, dynamic imaging plays a direct role in the effort to build patient-specific models of normal organ and body function [97]. CT will continue its expansion into the imaging of physiology and kinesiology. In this role, CT dynamics will be a cornerstone of functional imaging applications and will provide new insights into clinical diagnoses and improve patient care.

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