Published in final edited form as:
J Cardiovasc Comput Tomogr. 2009 ; 3(6): 403–408. doi:10.1016/j.jcct.2009.07.003.

What are the basic concepts of temporal, contrast, and spatial resolution in cardiac CT?

Eugene Lin, MD[a,*] and **Adam Alessio, PhD**[b]

[a]Department of Radiology, Virginia Mason Medical Center, 1100 Ninth Avenue, Seattle, WA 98111 USA

[b]Department of Radiology, University of Washington Medical Center, Seattle, WA, USA

Abstract

An imaging instrument can be characterized by its spatial resolution, contrast resolution, and temporal resolution. The capabilities of computed tomography (CT) relative to other cardiac imaging modalities can be understood in these terms. The purpose of this review is to characterize the spatial, contrast, and temporal resolutions of cardiac CT in practical terms.

Keywords

Computed tomography; Coronary arteries; Heart

Introduction

An understanding of the basic concepts of temporal, contrast, and spatial resolutions in cardiac computed tomography (CT) is necessary for the trade-offs involved in clinical cardiac CT imaging and in defining the role of CT relative to other imaging methods (Table 1).[1,2]

Spatial resolution

The spatial resolution of CT is excellent and the primary strength of the modality. Current CT scanners have a spatial resolution of 0.5–0.625 mm in the z-axis, and approximately 0.5 mm in the x- to y-axes. A basic requirement for adequate multiplanar reconstruction is that the resolution is isotropic; eg, the resolution is approximately equal in all directions. The resolution of CT is superior to the resolution of magnetic resonance imaging (MRI), which is typically 1–2 mm for most sequences and more than adequate for most clinical applications of CT. However, the current resolution of CT is not optimal for precise stenosis grading of the coronary arteries, which measure in the 5-mm range proximally, and ≤2 mm distally. Thus, in a distal coronary artery, there may be no more than 4 CT voxels, which does not allow for precise grading of stenosis. In addition, the current resolution of CT only allows for accurate plaque densitometry of relatively large plaques (≥50% of vessel

* Corresponding author. radecl@vmmc.org.

Conflict of interest: The authors report no conflicts of interest.

diameter).[3] Improvement in spatial resolution, possibly with new methods such as fine-detector or high-definition CT, will allow for more accurate stenosis grading and for the ability to perform plaque densitometry in smaller plaques.

Flat-panel volume CT scanners have superior spatial resolution and a wider volume of coverage than does multidetector CT.[4,5] The isotropic spatial resolution of flat-panel volume CT is 0.2–0.3 mm. The contrast resolution is slightly inferior to multidetector CT. Currently, the main disadvantage of flat-panel volume CT systems is substantially inferior temporal resolution (gantry rotation time of approximately 2 seconds), which is an important limitation for cardiac studies.

Contrast resolution

The contrast resolution of CT is not intrinsically high, because the difference in x-ray attenuation between different tissues is generally small (Fig. 1). The contrast resolution of CT is inferior to that of MRI and substantially inferior to single-photon emission CT or positron emission tomography (PET). Because contrast resolution is the primary requirement for molecular imaging technologies, CT is not currently an adequate method for molecular imaging, although it can often be fused to molecular imaging methods for anatomic localization (eg, positron emission tomography/CT).

The relatively limited contrast resolution of CT suggests that MRI may be intrinsically superior for many cardiovascular applications. For example, CT can detect delayed enhancement of myocardial infarcts, but the enhancement will be better visualized on MRI, where the normal myocardial signal can be nulled. CT can evaluate noncalcified plaques by differences in attenuation, but the absolute differences in attenuation between lipid-rich and lipid-poor plaques are minimal. MR techniques for plaque evaluation can have substantially greater contrast resolution. One approach to plaque evaluation on MRI is to evaluate for macrophage infiltration of unstable plaques with iron oxide particles that are phagocytized.[6] The resulting loss of signal in the plaque results in a substantial difference in MRI signal compared with plaques without iron oxide uptake.

The primary way to increase contrast resolution on CT is to administer intravenous iodinated contrast. With the administration of iodinated contrast, contrast resolution in areas with a high concentration of contrast relative to surrounding structures, such as the coronary arteries, can be high. The contrast resolution of CT can be optimized by increasing the attenuation of administered intravenous contrast (for CT angiography [CTA]) and by decreasing image noise.

Intravascular contrast attenuation can be optimized with proper timing, high iodine flux, and adequate contrast volume.[7] Iodine flux is increased by increasing the iodine concentration, the rate of injection, or both. Arterial enhancement is negatively correlated with patient weight and positively correlated with contrast volume. However, once contrast volume is adequate, further increases in volume may not increase enhancement. Although greater intracoronary attenuation during coronary CTA leads to higher diagnostic accuracy in evaluating stenosis, high degrees of enhancement may not always be optimal for coronary CTA. With high degrees of enhancement, the density of contrast may overlap that of coronary artery calcium and obscure calcified plaques. In addition, plaque densitometry is more optimally performed with relatively low degrees of enhancement (250 Hounsfield units),[3] because high degrees of intracoronary attenuation can artifactually increase plaque attenuation.

Another way to optimize intravascular contrast attenuation is by decreasing the tube voltage (to 100 or 80 kV),[8] which may increase the opacification of blood vessels because of an increase in the photoelectric effect at lower tube voltages. This will also decrease radiation dose. However, image noise will increase, which may mitigate the effect of the increased vascular opacification.

Because of radiation dose concerns, it is difficult to increase contrast resolution during cardiac CT by decreasing image noise. Because many techniques increase image noise, the focus is on application of these techniques while maintaining adequate image quality. Techniques to reduce radiation dose such as lowering tube voltage or electrocardiogram-dependent tube current modulation will increase image noise. Edge-enhancing filters can be used to decrease blooming artifact and are better to evaluate stents,[9] but these will increase image noise. Because images from large patients will be noisier, it is difficult to use edge-enhancing filters or some techniques tor reduce radiation dose in large patients.

Dual-source CT scanners can perform simultaneous data acquisition with the tubes operating at different voltages, known as dual-energy CT. This offers the possibility of improved tissue differentiation (eg, allowing tissue subtraction)[10] and thus improved contrast resolution.

Temporal resolution

Temporal resolution is the ability to resolve fast-moving objects and is comparable to shutter speed for a camera. For most applications of CT, temporal resolution is of little importance because the structures imaged have minimal or no motion. However, it is vital during cardiac CT, particularly for evaluation of the coronary arteries that are only optimally imaged when there is the least cardiac motion. This occurs during the so-called rest periods, which is typically in mid diastole (diastasis). Coronary motion is also minimal during end systole (isovolumic relaxation), but this is of shorter duration than diastolic diastasis at low heart rates. As heart rate increases, diastole shortens relative to systole, and diastasis shortens dramatically. The optimal reconstruction window transitions from diastole to systole at ~75–85 beats/min.[11] The cardiac rest period, if defined as the time with a coronary artery displacement of <1 mm, has a mean duration of 120 milliseconds, but ranges from 66 to 333 milliseconds.[12] Thus, very high temporal resolution is needed at high heart rates, because the diastolic and systolic rest periods are shorter in absolute terms, and the diastolic rest period is also short in relative terms.

The current best temporal resolution of single-source CT (w135 milliseconds) and dual-source CT (w83 milliseconds) does not approach the temporal resolution of angiography (1–10 milliseconds).[13] It is inferior to the temporal resolution of MRI (20–50 milliseconds),[14] which can be performed without β-blockers. Note that temporal resolution on a MRI study is a flexible parameter that can be altered if necessary as a trade-off for imaging time. For example, if a patient cannot hold his or her breath well, the imaging time of a cine cardiac MRI sequence can be decreased by decreasing the temporal resolution.

High temporal resolution in cardiac CT is primarily achieved through fast gantry rotation time and partial scan reconstruction.[13,15] Current generation CT scanners have minimum gantry rotation times of ~270 milliseconds. Because faster gantry rotation times result in higher G forces, substantial improvements in gantry rotation times are unlikely. For noncardiac applications very high temporal resolution is not necessary, and images are reconstructed from a full 360-degree rotation of the gantry. For cardiac CT, a 270-milliseconds temporal resolution is not adequate, and partial scan reconstruction from a 180-degree gantry rotation (plus the fan beam angle) is used. The use of partial scan reconstruction will almost double the temporal resolution, to ~135 milliseconds.

The need for high temporal resolution in cardiac CT has a cost.[13,15] During a retrospectively gated helical study, all phases of the heart should be seen by the detector at any z-axis location. If the gantry is rotating quickly, the table cannot also move quickly, or there will be gaps in the acquired data. Thus, the need for high temporal resolution in cardiac CT requires a low pitch, which increases radiation dose (radiation dose and pitch are inversely related). At higher heart rates, the R-R interval is shorter, and it takes less time to acquire data from all phases of the cardiac cycle. The pitch can be increased, which will decrease radiation dose (Table 2). The relation between pitch, R-R interval, and rotation time can be approximated as pitch ≤ rotation time/R-R interval.[15] However, single-source CT scanners typically do not have the temporal resolution in partial scan mode to image at high heart rates. Single-source CT scanners typically need to use multisegment reconstruction to increase temporal resolution at high heart rates, which does not allow for increased pitch (and decreased radiation dose).

Multisegment reconstruction is often used to increase temporal resolution for imaging at higher heart rates.[13,16] In this technique, the data required for image reconstruction is selected from multiple sequential heart cycles (Fig. 2). In 2-segment reconstruction, the temporal resolution in doubled.

Multisegment reconstruction has several disadvantages.[13,16] Multisegment reconstruction is only effective in improving temporal resolution at specific heart rates (the heart rate and gantry rotation time need to be desynchronized). For data from ≥ 1 cardiac cycle to be used for image reconstruction, the same position has to be covered by the detector during consecutive cardiac cycles. Thus, the pitch has to be lowered, which will increase radiation dose. Multisegment reconstruction is optimal with a regular heart rate, because the same phase of consecutive cardiac cycles needs to be sampled. Irregular heart rates will result in slightly different phases of the cardiac cycle being sampled; this results in a stair-step artifact on single-segment reconstructions but will be averaged out during multisegment reconstructions and appear as image blurring. Even if the same phase of the cardiac cycle is sampled, the heart may not follow the same motion pattern from beat to beat, which can also cause image blurring. In one study,[16] two-segment reconstruction improved image quality at heart rates > 65 beats/min but did not increase diagnostic accuracy.

Dual-source CT technology is another way to increase temporal resolution.[17] A dual-source CT contains 2 tube/detector sets, arranged at 90-degree angles to each other. With 2 tubes, only a quarter gantry rotation is needed if partial scan reconstruction is used. Thus, the 165-milliseconds temporal resolution of single-source scanner with partial scan reconstruction can be halved to ~83 milliseconds. The higher temporal resolution of dual-source CT allows coronary CTA to be performed at higher heart rates without b-blockers. In one study,[18] dual-source CT yielded diagnostic quality images in patients with heart rates ranging from 71 to 108 beats/min (mean, 89 beats/min), with no difference in image quality in this range. Dual-source CT has also been used to obtain diagnostic quality images in patients with atrial fibrillation.[19,20]

High temporal resolution is very helpful for optimal application of various techniques to reduce radiation dose. One specific advantage of dual-source CT scanners over single-source scanners is that multisegment reconstruction is not needed at higher heart rates, and pitch can be increased at high heart rates to decrease dose. A commonly used dose reduction technique is electrocardiogram-dependent tube current modulation, where the tube current is reduced during specific phases of the cardiac cycle. Substantial dose reduction is possible with prospectively triggered sequential scans,[21] when the entire cardiac cycle is not imaged. With these techniques, if additional reconstructions are needed in other cardiac phases, these may be very suboptimal with tube current modulation and not possible with prospective triggering. Higher temporal resolution makes it less likely that additional reconstructions would be needed. Prospectively triggered techniques are optimally used at low heart rates because of the narrowly predefined reconstruction window; high temporal resolution increases the maximum heart rate at which prospective triggering is possible.

Besides dual-source technology, the other main recent advancement in cardiac CT technology is an increase in the number of detector rows. A 320-slice scanner has a craniocaudal coverage of ~16 cm, which allows the heart to be scanned in one gantry rotation and one heart beat. This technology is optimally used with the prospectively triggered sequential scan technique. This technique decreases radiation dose, and, if the data can be acquired in one heartbeat, phase misregistration artifacts arising from irregular heartbeats should not be an issue. It is still helpful to lower the heart rate, because a narrower phase window can be used to reduce radiation dose.[22] Increased temporal resolution would still be helpful with a 320-slice scanner, because it would allow the use of a narrow phase window at relatively high heart rates.

Conclusion

Cardiac CT is characterized by excellent spatial resolution, adequate temporal resolution, and relatively poor contrast resolution. A disadvantage of cardiac CT relative to methods such as MRI or echocardiography is the use of ionizing radiation. The clinician and technologist must minimize radiation dose and at the same time maintain adequate spatial, contrast, and temporal resolutions. The strength of CT relative to other noninvasive methods is its excellent spatial resolution. This accounts for its strength in coronary artery evaluation. Further improvements in spatial resolution, which are possible with technologies such as flat-panel volume CT, will improve our ability to grade stenoses more precisely. The current maximal temporal resolution of CT, although inferior to MRI and substantially inferior to angiography, is adequate for coronary artery imaging at relatively high heart rates and is even possible in selected patients with atrial fibrillation. Further improvements in temporal resolution will be helpful in dose reduction, in patients with arrhythmias, and in assessment of cardiac function. The contrast resolution of CT is not intrinsically high, although intravascular contrast resolution can be achieved with the administration of iodinated contrast. Potential ways to improve contrast resolution include targeted contrast agents, dual-source technology, double-layer detectors, new detector materials, and iterative reconstruction techniques.[23] This may allow CT to perform better in applications that rely on contrast resolution such as myocardial perfusion and plaque characterization.

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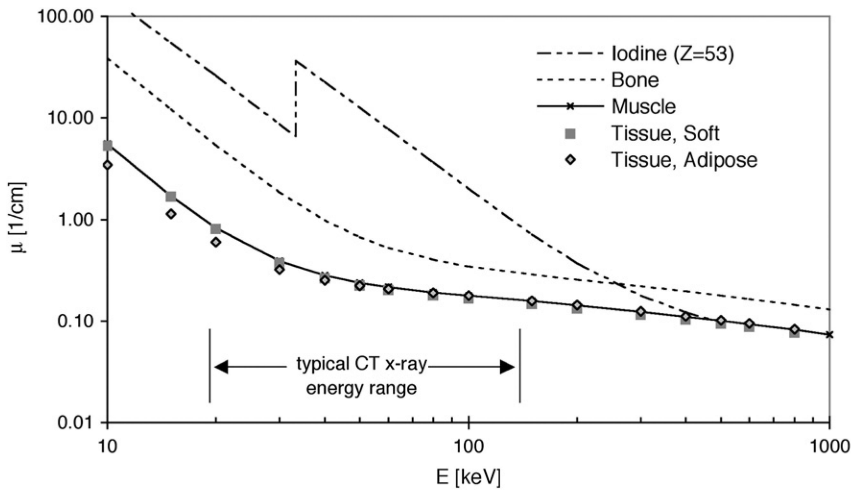

Figure 1.

Linear attenuation coefficient versus x-ray energy. For CT imaging, the body is imaged with x-rays in the range of 20–140 keV. In this range, soft tissues have little variation in their attenuation coefficients, leading to low soft tissue contrast and the need for contrast agents such as iodine.

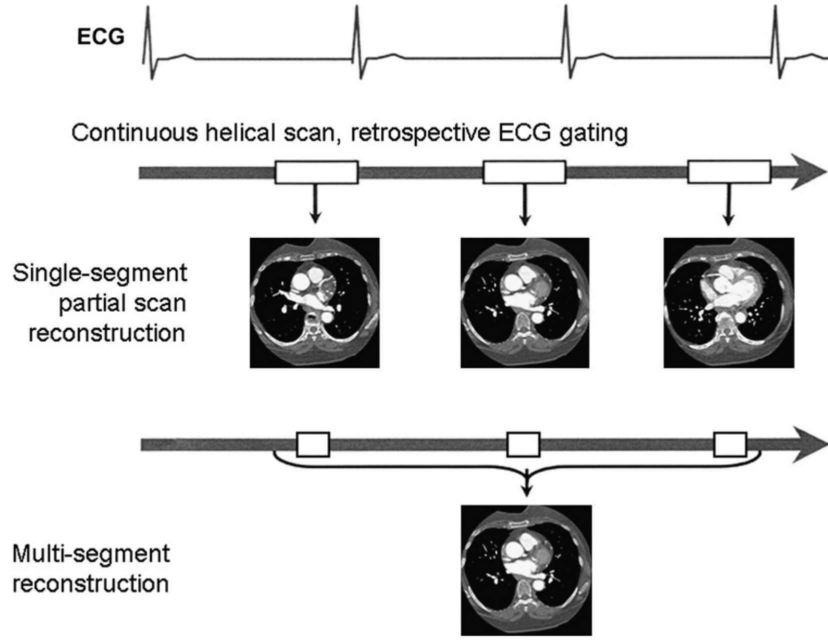

Figure 2.

Single-segment versus multisegment reconstruction. In single-segment reconstruction, an image is reconstructed from data from a prescribed time range in a single R-R interval. In multisegment reconstruction, the same image would be reconstructed from data from the same phase of multiple cardiac cycles, with a smaller time range (higher temporal resolution) in each R-R interval than with single-segment reconstruction. In the specific case shown in this figure, the temporal resolution would be increased by a factor of 3 with multisegment reconstruction.

Table 1

Spatial, contrast, and temporal resolutions of cardiac imaging methods

	Spatial resolution (FWHM), mm	Contrast resolution	Temporal resolution
CT	0.5-0.625	Low to moderate	83-135 ms
MRI	1-2	High	20-50 ms
Catheter angiography	0.16	Moderate	1-10 ms
PET	4-10*	Very high, varies†	5 s to 5 min*
SPECT	4-15*	Very high, varies†	15 min§
Echocardiography	~0.5-2‡	Low to moderate	>200 frames/s (<5 ms)

FWHM, full width at half maximum; PET, positron emission tomography; SPECT, single photon emission tomography.

*Depends on resolution versus noise tradeoff; higher count studies can be reconstructed with better resolution. Dedicated preclinical systems offer substantially improved resolution (<2 mm).

†Varies with specificity of radiotracer.

‡Intravascular ultrasound scanning can have a spatial resolution of 0.15 mm.[1]

§General purpose SPECT systems; Novel dedicated cardiac cameras offer improved temporal resolution on the order of 10 seconds to 5 minutes.[2]

Table 2

Interrelation of radiation dose, pitch, heart rate, and temporal resolution

	Single-source CT (lower temporal resolution)	Dual-source CT (higher temporal resolution)
Increased pitch	Decreased radiation dose	Decreased radiation dose
Increased heart rate	Decreased or increased radiation dose*	Decreased radiation dose

*The key interrelation is between radiation dose and pitch. Radiation dose decreases with increasing pitch. At higher heart rates, pitch can be increased, which decreases radiation dose. However, the situation may be different with a single-source CT scanner. The temporal resolution of the single-source CT may not be adequate for diagnostic quality imaging at higher heart rates. In these cases, multisegment reconstruction is often used. In multisegment reconstruction, the pitch is decreased, which increases radiation dose.