Radiology

Overcoming a Technological Hurdle: Coronary CT Angiography with Photon-counting CT

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In September 2021, the U.S. Food and Drug Administration (FDA) approved the first photon-counting CT scanner for clinical use. In their press release, the FDA stated: “The approval represents the first major technological advance in CT in nearly a decade.” We have never before seen that sort of announcement from the FDA about a new imaging test. Why does photon-counting CT excite a federal regulatory agency?

Let’s start with background. Photon-counting detectors were not initially developed for medical applications. The predecessor to medical photon-counting detectors was developed in the 1980s at the Conseil Européen pour la Recherche Nucléaire (CERN). The purpose of the original device was to detect particles resulting from high-energy collisions in the Large Hadron Collider located at CERN in Switzerland. That research resulted in the detection of multiple subatomic particles, including the Higgs boson (famously dubbed the “God particle”). Physicists at CERN realized that x-ray photons could also be detected with modification of the original particle detector technology. Instead of detector chips based on silicon, medical applications of photon-counting detectors are based on cadmium telluride, cadmium zinc telluride, or other proprietary combinations of materials.

Getting back to CT. We think of a CT scanner as a digital device—after all, we look at pixels all day. However, our conventional CT scanners use light and a photodiode to detect x-rays. The x-ray photon hits a solid-state detector, which “scintillates”—that is, the x-ray creates a brief flash of light. That light is collected by a photodiode placed adjacent to the detector. As more x-rays hit the detector, the light in the detector gets brighter. The photodiode outputs an electrical current, which is subsequently digitized and used to create our cross-sectional CT images.

The essential difference between imaging devices that contain photon-counting detectors versus conventional scintillating detectors can be conceptualized as digital versus analog. We all have digital TVs in our homes, and no one is going back to a tube TV. In this analogy, photon counting is digital. Like digital TV, photon counting is based on “chip” technology that uses exotic materials to detect the x-ray photon as present or absent—a stream of 0’s or 1’s like a computer. But photon-counting detectors can also do more: In addition to counting the number of x-ray hits on the detector, the energy of each photon can also be assessed (spectral imaging).

Several imaging devices have already been outfitted with photon-counting detectors, including digital mammography units, PET scanners, and bone densitometers. Although each of these has been shown to have advantages compared with conventional detector systems, the biggest impact of photon-counting technology will be in CT. This impact is due to the huge medical importance of CT scanners. Given the importance of CT in modern medicine—approximately 80 million CT scans per year are obtained in the United States—even a small degree of improvement will have substantial impact. In the case of photon-counting CT, these improvements are not expected to be small. The detector is the core of a CT scanner; the quality and character of the CT scan starts at the detector level. Photon-counting CT will bring increased resolution and precision and additional capabilities for multiple applications.

Our first glimpse of human capability of the modern photon-counting CT scanner was published in *Radiology* in 2016 based on research at our laboratory at the National Institutes of Health in Bethesda, Md (1). Using a prototype CT scanner developed by Siemens, we obtained iodine-enhanced CT images of the abdomen in human volunteers using both photon-counting detectors and conventional CT. In part, and to our surprise, the images from the two CT modes were reassuringly similar. This meant that relearning

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See also the article by Si-Mohamed and Boccalini in this issue.

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of the entire range of CT images would not be necessary for radiologists. Instead, the advantages of photon counting would be additive to existing technology. Those advantages include *(a)* always-on spectral CT, *(b)* the capability for doubling (or higher) spatial resolution, and *(c)* lower radiation dose. The interested reader who seeks additional technologic details about photon-counting CT is referred to the outstanding review article by Dr Willemink and colleagues (2)

Up to the present, however, there has been one core photon-counting CT application that was out of reach with the early prototype technology: coronary artery CT. Radiologists are well aware that CT scanners designed with coronary artery CT capabilities are both special and expensive. There are two demands for coronary artery CT that are unique compared with other areas of the body. The first demand is a wide area of scanning coverage. This demand resulted in the evolution of detectors with many rows of detector elements; 64 rows of detectors is barely sufficient, while 256 or 320 rows is more optimal. The use of 320 detector rows at 0.5-mm spacing results in 16 cm of z-axis coverage over the heart. This avoids the need to move the patient through the scanner gantry and allows single-heartbeat imaging.

The second unique demand for coronary artery CT is very high-speed imaging. How fast, and why? The heart is constantly moving, so coronary CT must be fast enough to capture a three-dimensional (3D) image of the heart without blurriness. MRI can easily provide a two-dimensional section of the heart in as little as half a second with very little effort. Unfortunately, a 3D MRI acquisition of the entire heart takes 3–5 minutes.

With our fastest conventional CT scanners, a 3D acquisition of the heart can be accomplished in one heartbeat with a dual-source or wide-detector CT scanner. For such rapid imaging, CT scanners required substantial engineering developments to allow the CT detector and x-ray tube to rotate rapidly around the patient. The gantry of the fastest CT scanners on the market rotates once every quarter of a second (250 msec) around the patient. At this speed, the centripetal forces on the mechanical components exceed 70 times the force of gravity—more than 70*g*. A structural failure at that force would send shards of metallic and electronic components flying through the building walls. We have seen that happen with an older CT device. Fortunately, the components moved outward away from the patient. Nevertheless, in the original human prototype CT scanner at the National Institutes of Health, Siemens cautiously reduced the speed of rotation of their prototype photon-counting CT system. In 2016, the concern was that the high *g*-forces required for cardiac CT would destroy the prototype photon-counting detectors.

Since that time, technology has progressed. New research by Si-Mohamed and Boccalini et al (3) in this issue of *Radiology* for the first time demonstrates the use of photon-counting CT in humans to image the coronary arteries.

What are we to expect from photon-counting CT for the coronary arteries? The earliest human application showed less image noise for photon-counting CT of the abdomen compared with conventional CT (1). A reduction in noise is fundamental to photon-counting detectors. A low energy threshold is inherent to the technology, virtually removing electrical noise from the detector. The approximately 30% lower noise level for photon-counting CT means that radiation dose can be lowered. This provides immediate benefits to all patients undergoing CT with these new devices.

The second expectation is higher spatial resolution. Although an advanced CT scanner by Canon with conventional scintillating detectors can produce pixels with 0.25-mm spatial resolution, most CT scanners produce pixels of approximately 0.5 mm or larger. Interestingly, whereas smaller pixel sizes become highly problematic for conventional detectors, smaller detector elements are inherent to photon-counting CT. For example, in the original prototype Siemens CT scanner, subpixel sizes were 0.12 mm. For various engineering reasons, only pixel sizes of about 0.25–0.5 mm were implemented. Because coronary artery CT is expected to depict vessels as small as 2 mm, making diagnoses of stenosis based on four 0.5-mm pixels is barely sufficient. The future of coronary artery CT is smaller pixel size.

The study by Si-Mohamed and Boccalini et al is exciting because we get our first glimpse of whether these promises of photon-counting CT can be fulfilled. The authors performed human photon-counting cardiac CT in 14 patients. Notably, all patients underwent scanning with standard CT and photon-counting CT. The authors performed a detailed comparison using subjective assessment of cardiovascular features that overwhelmingly favored photon-counting CT. The detail shown in the example images is startling, with thin ventricular trabeculations and valvular features displayed in superb detail. The capability of resolving this level of detail in addition to lower radiation is important. Still to be evaluated will be the spectral capabilities of the new device (4).

The authors' timing could not be better. The proven diagnostic capabilities for CT in the cardiovascular field have substantially increased in recent years. Radiologist-performed coronary CT has correspondingly increased by 355% from 2010 to 2019 (5). The benefit of coronary artery CT is now reflected in recently published joint guidelines for chest pain: Coronary artery CT received the highest level of recommendation and evidence for intermediate-risk patients with acute chest pain, a large portion of patients presenting to the emergency department with chest pain (class I, level of evidence A [6]).

For noncardiac imagers, photon-counting CT has similar promises. This technology will take time to spread, but the inventiveness of the imaging community is profound. For the chest imager: Would you be interested in double spatial resolution? Have you ever visualized the bronchial artery wall, where most lung disease takes place? For neuroimagers: CT is essential for acute stroke evaluation. Artificial intelligence is already prominent in this area but will get even better due to lower noise levels and spectral capability for better gray matter–white matter contrast; angiography and perfusion study quality will improve foreseeably. Abdominal imagers will have the opportunity to simultaneously evaluate multiple contrast agents at high spatial resolution (7).

In the past 30 years, we have experienced helical CT, wide-detector CT, and spectral CT. Each time, it seemed CT may have peaked. Once again, CT has reinvented itself with photon-counting detectors.

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