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News & Highlights

Innovative Scanners Boost Medical Imaging Quality and Utility

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During his 30-year career, radiologist Philippe Douek has pored over thousands of images produced by computed tomography (CT) scanners, looking for signs of illness or injury. But the professor of radiology at the University Claude Bernard Lyon 1 in France, was wowed by the performance of a new type of device known as a photon-counting detector (PCD) CT scanner. Douek and his colleagues have been putting prototype PCD machines through their paces, scanning animals, imaging dummies, and even Douek's lungs. The images produced with the technology "are much more detailed," he said.

The researchers have also demonstrated that this improved resolution pays off for patients. In a study performed in 2021, for instance, Douek and his colleagues found that a photon-counting scanner was superior to a conventional CT device for revealing coronary artery disease, the narrowing of the arteries that deliver blood to the heart [1]. "You can make the diagnosis of coronary artery disease with more confidence," said Douek.

PCD CT technology is now moving beyond research studies and starting to reach hospitals and clinics. In the autumn of 2021, the Food and Drug Administration (FDA), the US government agency that regulates drugs and medical devices, for the first time cleared one of the scanners, a model made by the German company Siemens (Fig. 1) [2]. The same model is also approved for clinical use in Europe and the United Kingdom. Other big-name medical imaging companies, including General Electric of the United States, Philips of the Netherlands, and Canon of Japan, are developing similar scanners that could reach the market soon. "This is a revolution in technology, not just an incremental improvement," said Shuai Leng, professor of medical physics at the Mayo Clinic in Rochester, MN, USA.

Another medical scanning mainstay, magnetic resonance imaging (MRI), could also be on the verge of dramatic machine evolutions that could make the technology suitable for more clinical settings. In August 2020, the FDA approved commercial sales of a portable MRI scanner, a machine made by the US company Hyperfine that features a 64 mT magnet (Fig. 2) [3]. In comparison, hospital MRI scanners can employ magnets more than 100 times stronger [4]. Smaller, cheaper, and easier to deploy than traditional MRI scanners, ultra-low field scanners like the Hyperfine device could make MRI available to more patients in developed countries and spread the technology to parts of the world that currently

Fig. 1. The Siemens' NAEOTOM Alpha is the first PCD CT scanner approved by regulatory agencies for commercial use. The device features two cadmium-telluride detectors and can reach a spatial resolution of 0.11 mm. The scanner's two X-ray tubes provide a temporal resolution of as little as 66 ms, making it easier to image the beating heart. Credit: Siemens (public domain).

Fig. 2. The Hyperfine ultra-low field MRI scanner was designed to image the brain. The patient's head fits into the opening and rests in the clear plastic cradle, known as a head coil, which detects the radio frequency (RF) energy emitted by the patient's tissues. The red object atop the scanner, called a Gauss guard, indicates the boundary beyond which the device's magnetic field will not attract metal objects or interfere with pacemakers. Credit: Hyperfine (public domain).

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cannot afford it [5]. Most notable for the clinical setting, they are small enough to be portable.

PCD CT scanners share some similarities with conventional CT machines. Both kinds of devices reconstruct images by firing a beam of X-rays through a portion of a patient's body [6]. Different tissues have different densities and absorb or scatter the X-ray photons passing through them to varying degrees [7]. For instance, bone is much denser than fat and attenuates an X-ray beam by a much larger amount [7]. When the photons reach the device's detector, how much their intensity has decreased indicates the density of the tissue they have traversed, and software constructs a CT image from that data [7].

The key difference between the two types of CT scanners is their detectors [8]. PCD scanners feature semiconductor detectors typically made of silicon, cadmium telluride, or cadmium zinc telluride that register each X-ray photon that reaches them [9]. In contrast, the solid-state detectors of traditional CT machines use a roundabout mechanism to measure X-ray beam attenuation. The detectors contain a layer of cadmium tungstate or other material that emits light when X-rays hit it [9]. A photodiode then detects these flashes. Unlike a PCD CT scanner, which gauges the energy of individual photons, a conventional CT scanner sums the energies of thousands of photons that arrive within a given time [8,10].

The most obvious benefit from PCD technology is improved image quality. The pixels on the detector of a photon-counting device can be smaller than on the detector of a conventional CT scanner [9]. As a result, a PCD CT scanner "can provide two to three times better spatial resolution, and we can see more details of anatomy and pathology," said Leng. The new technology offers other advantages as well. PCD devices diminish artifacts created by dense bone or metal implants, such as stents and artificial knee joints [9,11]. Most traditional CT devices can simultaneously scan patients with photons of two energies, allowing radiologists to determine the composition of different materials in the body, such as kidney stones and the uric acid crystals that cause gout [9,12]. However, a PCD machine can scan the patient with multiple energies of X-rays at the same time, providing more discriminating power. For patients, a big plus is that they receive as much as 45% less radiation during a scan [8].

Overcoming additional technical challenges could provide even better PCD imaging. For one thing, at a given radiation dose, higher spatial resolution imaging increases image noise, as the number of photons captured by each detector is reduced, an issue that affects both PCD and traditional scanners. To capitalize on the ultra-high-resolution capability of PCD CT, Leng and other researchers are investigating whether artificial intelligence (AI) or other approaches can mitigate the noise. Another challenge for PCD CT machines is that, at least initially, they are likely to cost more than traditional CT scanners, which can run up to 3 million USD [13].

Nonetheless, Leng predicts that PCD scanners will eventually replace conventional CT machines. The devices could also reduce the need for certain invasive procedures, said Douek. For example, to determine whether a patient's coronary arteries are obstructed, cardiologists often perform a procedure called coronary angiography, which involves inserting a catheter into an artery in the patient's groin or arm and steering it to the heart [14]. The catheter then releases dye that enables the cardiologist to discern narrowed arteries on an X-ray. However, PCD CT non-invasively provides crisp images that reveal the state of the coronary arteries, Douek said. "It could replace coronary angiography."

Unlike CT devices, which map the density of particular tissues, MRI differentiates structures by how much water they contain. An MRI machine's magnet causes hydrogen nuclei, such as those in water molecules, in the scanned portion of the patient's body to line up with the device's magnetic field [15]. To produce an image, the machine sends out radio frequency (RF) waves that bump the hydrogen nuclei out of alignment. The device then shuts off the RF signal, allowing the nuclei to relax, or return to their original orientation. In the process, they release energy at different rates depending on the type of tissue in which they reside, and the machine measures this energy and uses it reconstruct the anatomy [16].

Except for a few models for specialized applications such as orthopedics that have magnets of less than 1.0 T, most of today's MRI scanners boast 1.5, 3.0, or 7.0 T magnets. They are invaluable for diagnosing many illnesses and injuries, but they are also expensive behemoths that need specialized infrastructure. Their superconducting magnets can weigh up to 4500 kg [17]. If the magnets stop superconducting, the low-temperature, liquid helium that cools them can boil off, so the devices must have a ventilation system to route the gas outdoors [17]. Two types of shielding are also necessary to prevent interference. Because MRI magnets are so strong and could disrupt nearby electronic equipment, the machines are installed in rooms lined with magnetic shielding, typically steel plate [18]. The walls, ceiling, and floor of MRI rooms are also usually clad in copper or galvanized steel to prevent external electromagnetic signals from interfering with the scanner's detectors [19]. MRI devices typically cost around 1 million USD$\cdot$T^{-1}; with hospitals increasingly deploying more 7 T machines, the price tag continues to grow [20,21].

The size, cost, and infrastructure requirements of conventional MRI scanners restrict where they can be located and how they can be used. Hospitals typically place the one or two machines they can afford in a central location, and as a result MRI scanning often becomes a bottleneck for care, said Mathieu Sarracanie, professor of biomedical engineering at the University of Basel in Switzerland and a co-founder of Hyperfine. "MRI is like a phone booth—you need to wait to get a slot." Moreover, patients who are too ill to be moved cannot benefit from the technology, said Eliot Siegel, a professor of diagnostic radiology and nuclear medicine at the University of Maryland School of Medicine in Baltimore, MA, USA.

MRI scanners are also out of reach for many hospitals and clinics in less-developed countries. A survey published in 2018, for example, found that there were only 84 MRI machines in all West Africa, which translates into 0.2 devices per million people [22]. In Japan, the country with the world's highest rate, there are 55 scanners per million people [23].

Interest in developing simpler, cheaper, albeit less flexible, MRI machines is not new, but the field is surging, said Sarracanie. Low-field devices with magnet strengths less than 1 T are on the market and overcome some of the limitations of more powerful MRI machines. Siemens' 0.55 T scanner, which the FDA cleared in 2021, requires less helium coolant, does not need an exhaust system, and can fit into a smaller space than a traditional MRI device [24]. Still, at nearly 3200 kg, it is not portable.

Ultra-low field devices, which generally have magnets of less than 0.1 T, may provide better options for increasing access, simplifying infrastructure, and reducing costs, said Sarracanie. Most ultra-low field MRI devices, including the Hyperfine and University of Hong Kong machines (see below), are designed to image the brain—one of the most frequent applications for MRI—or extremities such as the hand. Machines that can image the whole body, Sarracanie said, are less appealing because they require larger magnets, an obstacle to portability.

The Hyperfine scanner is the first portable device to receive government clearance. Resembling an industrial vacuum cleaner, the scanner is 150 cm tall, 84 cm wide, and weighs 635 kg [25]. It boasts relatively weak permanent magnets, not the powerful superconducting magnets found in traditional MRI scanners, and as a result does not require an expensive helium cooling system or a specialized shielding room [26]. Also, unlike traditional MRI machines, the Hyperfine scanner can be wheeled to a patient's bedside to, for instance, quickly diagnose strokes [27].

Smaller, mobile MRI scanners like Hyperfine's could alter the technology's medical role in the developed countries, said Siegel, who is on Hyperfine's advisory board. The devices could become standard equipment in operating rooms, emergency departments, and other locations where they are now impractical—even including ambulances, he said. How doctors use the technology could change as well, he added. They may be able to track changes in a patient's condition by performing repeated scans, which are usually not possible now because of long wait times.

The scanners are much cheaper than their traditional counterparts. The Hyperfine device costs around 50 000 USD [4], and even less expensive designs might be possible. In 2021, for instance, a team of researchers at the University of Hong Kong revealed a boxy portable machine that they estimate would cost under 20 000 USD [5,17]. Such economical devices "could be a complete game changer in parts of the world where MRI is not available," said Siegel. Hyperfine projects having more than 80 of its scanners installed and operating by the end of 2022 [28].

Ultra-low field devices face skepticism in developed countries, however, with some US insurance companies refusing to pay for scans made with machines with magnets that are less than 0.3 T, Siegel said. And while critics worry that the devices generate images with lower resolution, that concern is unfounded, Sarracanie said: "A higher field strength does not give you more resolution or a better image per se. It gives you a higher signal-to-noise ratio per unit time." Researchers are developing strategies to counteract the higher noise of the ultra-low field images, like the deep-learning AI algorithms used by the Hyperfine scanner and the University of Hong Kong prototype [17,26]. But ultra-low field devices likely will not match the image quality of the larger machines, Sarracanie said. "Are we ever going to be able to produce images as crisp as high-field scanners in the same amount of time? The answer is no. But image quality is progressing at a fast pace, and we can already do imaging that is clinically relevant."

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