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PERSPECTIVES

The Industry of CT Scanning

Let's recap: CT was invented in 1972 by Godfrey Hounsfield of the EMI Laboratories in England and by Allan Cormack of Tufts University in the United States. In 1979, both shared the Nobel Prize for its invention. The first commercial units (1974) were for head imaging only and acquired data only 1 section at a time, which, in turn, took hours to reconstruct. Two years later, whole-body scanners became available. In 2007, 72 million CT scans were done just in the United States.[1] No one knows exactly how many machines have been sold, but numbers vary between 6000 and 7000 in the United States (24–25 per million population) and probably more than 30,000 worldwide. The main limitations of medical CT are that the entire apparatus needs to rotate around the patient, resulting in complex mechanics and frequent calibrations, limited spatial resolution, and radiation exposure. Recently, spatial resolution has been hampered by increased noise due to lower radiation doses. Although when we think CT, we think radiology and medicine, its applications are more far-reaching and the business of scanning is no longer limited to medicine. Most of the limitations of medical CT are not shared by industrial CT as we will see. In this *Perspectives*, I will discuss some applications of CT scanning outside of medical imaging.

The major industrial applications of CT include research, inspections, attenuation analysis, reverse engineering, measurements, and 3D digitization. The industry refers to inspections using CT as "NDT" (nondestructive testing), and there are many companies offering this service. (There is even an American Society of Non-Destructive Testing [http://www.asnt.org]). NDT is essential when lightweight materials such as aluminum are used for high-stress-resistant structures like honeycombs. Honeycombs offer great structural integrity at a fraction of weight compared with other materials, but with stress, they may fracture (generally hairline-type fractures). Because honeycombs are used in essential parts of airplanes (engines, exhausts), they need to be checked regularly, and CT scanning is a great way to do this. NDT is also used for examinations of gasoline-burning motor castings and plastic and composite materials. Molds can be scanned, and information obtained may be used to assess integrity and for duplication.

Apart from aerospace, aviation, and automotive applications, industrial CT may be used to inspect the inside of electronic equipment such as radios, and because of its extreme spatial resolution, some machines are capable of imaging the inside of computer chips and cables that conduct electricity or optical fibers. In museums, CT scanners are commonly used for the examination of skeletal remains, mummies, vases, and other artifacts. In dental science, industrial micro-CT allows 3D visualization and extremely accurate measurements of dental implants and prostheses. Pharmaceutical companies use it to image the inside of tablets and capsules and to assess the internal components of different apparatuses such as asthma inhalers. Foods may be inspected, and one commonly sees this application in airports where the Department of Agriculture scans luggage looking for food and then scans the products that are uncovered. Metrologists (scientists specializing in the science of measurements) use CT scanning routinely.

Industrial micro-CT is a different ballgame than human CT scanning. One rotation may take up to 1 hour in duration but results in images with resolutions between 1 and 10 μm, depending on the system (generally their resolution is more than 100 times better than that found in the best medical CT units; remember that it takes 10,000 μm to make 1 cm). Total scanning time is generally between 45 minutes to 5 hours, though newer generations of these machines can scan simple objects in a matter of seconds. The part to be scanned is placed inside a chamber on a rotating platform (in some scanners, parts that have been scanned are removed and exchanged for others by using robotic arms, which is faster than doing it manually). This is one of the main differences between industrial and medical CT scanning. In the former, the object rotates; in the latter, the x-ray equipment does. Rotating the x-ray tube and detectors limits acquisition speed and leads to loss of calibration and the need for frequent adjustments.

In industrial CT units, the scanning chamber size varies, but it tends to be relatively small compared with what we radiologists are used to (in our scanners, the gantry opening is the equivalent of this chamber). Because industrial materials may be very dense, these machines use significant doses of radiation (450 kV is typical), and megavolt units are capable of penetrating up to 400 mm of steel. Typical industrial scans produce anywhere between 360 and 3600 images "weighing" about 2 GB in total. Industrial scanning companies also offer 3D reformations, and their computers are capable of processing billions of voxels in just a few seconds.[2] The price for each of these systems varies between US $300,000 and $5 million. I was not able to find what an individual study costs as most companies require a consultation before giving you a price estimate.

For many years, industry has used laser scanners to obtain exact measurements, but these offer only external evaluations, whereas CT is capable of external and internal analysis. This has lead to industrial CT being extensively used in the field of reverse engineering, which is the process of discovering the technologies used by humans to build things. Reverse engineering is commonly used in industrial espionage, and the military use it extensively to study and copy products of other countries. One of the most intriguing applications is reverse engineering of the brain. Developers of artificial intelligence pay close attention to the way that our brains (or those of animals) are engineered and try to copy parts of these. It is hoped that this activity will extend to the physiologic activities of the brain and that models of brain-medication interactions will be designed and studied,[3] resulting in better treatments. Reverse engineering of the human body has lead to the development of improved extremity prostheses, artificial retinas, and other neural prostheses (such as cochlear implants).

The other area where industrial CT is commonly used is rapid prototyping (solid free-form fabrication). This refers to the use of CT data in the construction of physical objects (models and prototypes). When consecutive layers of materials are added to make objects from 3D data, one is said to be doing additive manufacturing; the reverse is called subtractive manufacturing. Rapid prototyping is also used by artists, sculptors, and jewelers to produce complex shapes. It is ex-

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pected that in the not-so-distant future, rapid prototyping will allow one to create objects at home. In the world of nanotechnology, rapid prototyping is used for structure design, simulations, interfaces, patterning, and other manipulations from simple molecules at the atomic scale to complex nanodevices. Nano-CT scanners are a new type of device with spatial resolutions of around 400 nm. One manufacturer claims to be able to image individual osteocytes in a mouse fibula. Carbon nanotube CT scanners will probably be cheap, work at room temperatures, be very fast, have no moving parts, and be of different sizes, some small enough to be deployed to war theaters and space.[4]

Contrary to popular belief, airports do not routinely use CT equipment to scan luggage. Most luggage scanners are simple x-ray machines that assign different colors (generally 6) to objects according to their atomic numbers (you may remember from your physics courses that the atomic number is the number of protons in the nucleus of an atom). The so-called CTX scanners are used specifically to discover explosives. These units are very similar to ours—that is, the luggage remains static in a gantry and an x-ray tube rotates around it at 120 revolutions per minute (in the fastest of these machines), generating an image every 0.5 seconds and scanning up to 560 bags per hour. When CT scanning becomes available at the passenger security checkpoints, 3D reformations may allow identification and internal examination of portable computers, and these should no longer need to come out of our bags. CT scans of passenger luggage are essential when a person gets "flagged" as high risk.

When one's body is scanned at the airport, images are obtained with "backscatter" (narrow and low-attenuation beams) or radio-frequency energy (millimeter wave) or with whole-body "advanced imaging technique" (AIT) scanners that are very similar to conventional CT scanners.[5] Both scanners create a 3D surface image of the body that some believe violates individual privacy (though genitals are hidden from view). Studies have found that backscatter scanning is safe for the general public, even for children who are more sensitive to radiation exposure than adults.[6] These scanners use a very low-level millimeter-wave nonionizing radiation that does not penetrate the skin (there is debate if this type of radiation is harmful to individuals predisposed to skin cancers, and because most of the radiation strikes the head where 85% of basal cell cancers occur, the risk may be real). The dose received is equivalent to that of flying 2–3 minutes at 30,000 feet on a commercial airplane according to the American College of Radiology.[7] Between 1000 and 2000 of these scans are needed to reach the radiation level of a chest radiograph.[8]

AIT scanners do use radiation, and though the dose they deliver is safe per individual, it may not be safe to the population as a whole. Experts estimate that up to 100 new cancers per year may occur secondary to radiation exposure at airport security posts in the United States alone. Because radiation is absorbed by the skin, children may be more sensitive to its effects than adults. What this radiation exposure will mean to unborn children is the concern of many mothers.[9] Although the total time needed to scan each passenger is between 8 and 15 seconds, radiation is delivered during only a fraction of a second. The long-term effects of being repeatedly exposed to low-level radiation (which would a problem for pilots who are scanned hundreds of times each year and additionally get the exposure from high-altitude flights) has not yet been ascertained. Curiously, accidental overdoses need not be reported.

Each of these machines costs about US $170,000 and as of this writing, there were 400 in 69 airports. A cost-benefit study of these machines has not been performed as the Transportation Safety Agency (TSA) states that the Department of Human Services does not require it. The cost of these scanners is staggering, about $336 million from the over $8 billion TSA budget. *USA Today* reported that airport scanner manufacturers doubled their lobbying expenditure in the last 5 years with a single company spending over $4.5 million.[10] As a traveler, you may refuse a body scan but not a full-body pat down in its place (to do so means that you will not be allowed to fly and may be fined $10,000). To put the quantity of airport scans needed to ensure air safety in perspective, remember that in 2010 more than 90 million passengers went through just the Atlanta airport (much more than the number of patients who got medical CT scans during the same period of time). It is expected that soon, 1 billion passengers will be scanned in the United States every year, and with exposure such as this to the population, there is a real risk for harm. In *America On-line News*, the TSA stated that the US Army, the US Food and Drug Administration (FDA), and The Johns Hopkins University were involved in assessing the safety of these scanners. Surprisingly, all 3 institutions deny this claim. Because airport scanners are not considered "medical," the FDA has no jurisdiction over them. The Health Physics Society has requested radiation data from TSA, only to have it denied several times. Congress has now called on the TSA to release these data for independent analysis but that has not occurred at the time of this writing. This issue becomes critical because new airport scanners that are able to do "cavity searches" are being developed, and these use penetrating radiation very similar to that used in medical CT scanners.

So, now you may stop wondering about why your CT salesperson does not visit you anymore or why these companies do not support our scientific meetings the way that they used to. The US medical CT market is basically saturated and that may soon happen in most other developed countries; why not go outside of medicine? Our regulatory agencies—quite adequately—are keeping a close eye on medical CT due to the recent radiation overexposure situations; why not go outside of medicine where radiation exposure is of no concern? Airports and maritime ports will soon be buying more scanners, but they are not obligated to report, justify, or explain their use (or abuse) to anyone as we are in medicine. The business of CT may not be growing in your practice, but you can rest assured that it is booming elsewhere.

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