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Editorial

Could imaging with monochromatic x-ray beams become a reality in all our hospitals?

X-ray beams used every day for imaging in our hospitals contain a wide range of photon energies. This is inevitable because of the way in which they are produced. Metal targets (e.g. x-ray tube anodes made of tungsten) are irradiated with beams of electrons and, although the electrons are monoenergetic, interactions with the metal generate Bremsstrahlung x-ray photons with energies extending from that of the incident electrons downwards. The electrons lose energy when they interact with the metal atoms as the beam penetrates the anode and x-rays produced from deep within the anode are attenuated as they leave. The net result is that a wide range of Bremsstrahlung x-ray energies are produced from the thick metal anodes with an intensity distribution that decreases with increasing photon energy.

Contrast between different tissues in medical x-ray images occurs primarily because of the photoelectric effect, which gives large differences in attenuation resulting from variations in elemental composition, since the photoelectric attenuation coefficient is proportional to the cube of atomic number. Compton scattering, the other interaction process, gives some differentiation in tissue attenuation, but this depends only on tissue density and the contribution to image contrast is more limited. The probability of photoelectric interactions declines as photon energy increases, so the relative contributions from the two interactions vary across the energy range. Although we might know what x-ray energy would give the best images when, for example, iodine contrast material has been injected into a blood vessel, we have to use our standard x-ray beams containing photons with these wide ranges in energy. But what if we could select the particular x-ray photon energies that result in optimal contrast? Studies using monochromatic x-rays generated from high intensity beams from synchrotrons have shown excellent contrast in mammographic imaging with significant reductions in dose (Burrattini *et al* 1995, Arfelli *et al* 1998). But synchrotrons are large and expensive. They are not suitable for use in hospitals, even if the National Health Service could afford them.

Characteristic fluorescent x-rays in narrow energy bands are emitted when transitions occur between electron energy levels. If tightly bound electrons are dislodged from inner atomic energy levels and are subsequently replaced by electrons from outer levels of the atom, x-rays within narrow energy bands that are characteristic of the particular metal are emitted. Electrons removed from the inner K-shell have the highest binding energies and so are the ones relevant for imaging. In a conventional x-ray tube some bound electrons are ejected from the metal atoms in the anode, and so some characteristic x-rays are produced. But their intensities are low compared with those of the broadband Bremsstrahlung x-rays, so they play an insignificant role in most x-ray equipment. But these fluorescent x-rays have the potential to provide narrow energy x-ray sources, if only we could remove the Bremsstrahlung.

A way to produce characteristic x-rays without Bremsstrahlung would be to excite bound electrons in a metal target with x-ray photons rather than electrons. However, this would require very intense x-ray beams. One of the limitations in x-ray tube technology arises from the need

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to focus the electron beam onto a small spot on the rotating anode in order to achieve the necessary resolution, but if x-rays are being produced to stimulate fluorescence in a target, rather than produce an image, the electron beam could be spread over a much larger area, and so allow higher outputs to be realised. The Bremsstrahlung produced could then be used to irradiate a thin target, and through this two-stage process, a source could be created in which the characteristic x-rays predominated.

A prototype monochromatic x-ray tube has been developed recently to generate fluorescence spectra from K-shell transitions using x-ray photons as the stimulus (Silver *et al* 2021). Its design is very different from a conventional broadband source. Bremsstrahlung x-rays are generated from within a relatively large, stationary, conically shaped anode with the electron beam power being distributed over a large area inside the cone. The Bremsstrahlung and characteristic x-ray emissions from the anode, made of gold-coated tungsten, irradiate a compact target in the form of a cone of thin foil, made of the metal for which the K-shell fluorescence is required. Although only Bremsstrahlung x-rays with energies greater than the binding energy of the K-shell electrons in the foil target are capable of generating K-fluorescent emissions, sufficient have been produced to demonstrate the feasibility of the method through imaging test phantoms.

The first use of the prototype x-ray tubes will be for mammographic imaging of the breast. It currently uses foils of silver or tin, which emit x-rays at 22 keV and 25 keV, respectively. These x-ray beams are almost monochromatic (>95%) and have energies that are ideal for imaging breast lesions, so they can give much improved signal-to-noise ratios and therefore better image quality for visualisation of low contrast masses or microcalcifications. The current system can more than double the signal-to-noise ratio at a similar radiation dose to current mammography systems. Depending on the breast thickness, it would also allow dose reductions of 5–10 times with appropriate image quality levels for diagnosis while maintaining similar signal-to-noise ratios to conventional systems. The group has also demonstrated that contrast enhanced digital mammography, which uses iodine contrast with subtraction of x-ray images at different energies, can be performed simply and effectively with monochromatic x-rays at substantially lower radiation doses.

The prototype monochromatic x-ray system is now at the laboratory testing stage, but already has a similar size and image field to conventional mammography systems. However, there are still technical issues to address. The efficiency is much lower than that of a conventional x-ray tube because of the two-stage emission process. Higher fluorescent intensities are needed before the current system has exposure times suitable for hospital use, since the exposure times are currently over 10 s. The research group is currently building a new system with a higher monochromatic flux that should give exposure times between 1 and 10 s.

Although there is still some way to go, development of this system is well on the way towards the clinical use of monoenergetic x-rays. Application to imaging applications other than the breast will require much higher photon fluxes and foil targets of metals with higher atomic numbers to penetrate thicker parts of the body. The group has already demonstrated the production of neodymium K-shell x-rays at 37 keV, which is just above the K-absorption edge of iodine contrast media and could have the potential for dramatically improving image quality for contrast studies and achieve substantial reductions in radiation dose. If monochromatic x-ray systems can be developed for use in mammography, it could mark the first step along the road to a new approach to x-ray imaging.

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References

Arfelli F *et al* 1998 Mammography of a phantom and breast tissue with synchrotron radiation and a linear-array silicon detector *Radiology* **208** 709–15

Burattini E, Cossu E, Di Maggio C, Gambaccini M, Indovina P L, Marziani M, Pocek M, Simeoni S and Simonetti G 1995 Mammography with synchrotron radiation *Radiology* **195** 239–44

Silver E H, Shulman S D and Rehani M M 2021 Innovative monochromatic x-ray source for high-quality and low-dose medical imaging *Med. Phys.* **48** 1064–78