Medical imaging with monochromatic X-rays

By Dr E Silver

This article summarizes the results of a recently published report on the successful development of a monochromatic X-ray tube for routine imaging in the clinic

It is well-known that X-ray imaging with monochromatic X-rays reduces the radiation dose and increases the signal-to-noise-ratio (SNR) of image features [1-6]. It may also help to spectroscopically determine *in vivo* the chemical composition of tumors and surrounding tissue. A recent publication in Medical Physics reported the development of a monochromatic X-ray tube suitable for routine use in the clinic [7]. The new tube can be fitted in all current X-ray and CT imaging systems and can potentially replace the ubiquitous century-old broadband X-ray technology.

While previous research studies using Bragg crystal monochromators coupled to either large synchrotron light sources or traditional broadband X-ray tubes [8-12] demonstrated the advantages of monochromatic X-ray imaging, neither technology is suitable for general clinical applications. The viability and performance of the new concept described in the Med Phys article [7] stems from its ability to produce a selectable monoenergetic X-ray energy spectrum with sufficient intensity over a wide field-of-view, enabling high quality images at low dose, all within the footprint of existing conventional mammography systems.

In its first application, the patented tube technology was installed into a laboratory prototype of a monochromatic X-ray mammography system. Image quality was evaluated as a function of radiation dose using the signal-to-noise ratio (SNR) measured for high and low contrast masses and microcalcifications in standard breast phantoms with a variety of thicknesses. Spatial imaging properties were assessed from these images as well as from modulation transfer analysis (MTF). Measurements using an iodine contrast agent were also performed.

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The results were compared to those obtained using a commercially available, conventional X-ray mammography system. The prototype system reduced radiation dose by factors of 5 to 10 times for the same SNRs as obtained from a conventional system. The high SNRs for very thick breast phantoms provide strong evidence that screening with lower breast compression is possible while maintaining image quality. In addition, Contrast Enhanced Digital Mammography (CEDM) with monochromatic X-rays was shown to provide a simpler and more effective technique at substantially lower radiation dose.

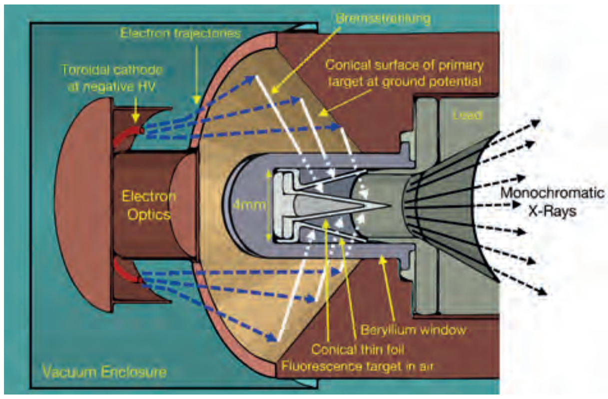

Figure 1. A 3D section of the prototype monochromatic X-ray tube. A toroidal cathode at negative HV emits electrons that follow trajectories, shown schematically in dark blue, that end on the inside surface of the conical metal target. Broadband X-rays from the conical target, shown schematically in white, pass through a beryllium window that seals the vacuum enclosure from atmospheric pressure. These X-rays interact with the conical thin foil metal to produce monochromatic X-rays via fluorescence

THE MONOCHROMATIC PROTOTYPE

The IP-protected technology combines two X-ray emission processes to generate monochromatic X-ray beams. As shown in Figure 1, the inside surface of a conically-shaped annular metal ring is bombarded with high energy electrons to emit broadband X-ray energies. These X-rays are concentrated onto a compact, thin-foil, metallic target placed at the center of the annular ring. The foil subsequently emits monochromatic X-rays via fluorescence with an energy that uniquely identifies its elemental composition.

An example of the fluorescence spectrum emitted by a foil target of tin (Sn) is shown in Figure 2. It consists of two monochromatic emission lines, one very strong Kα line at 25.27 keV and a much weaker Kβ line at 28.49 keV. The emission from the tin target is 96% monochromatic which means that only a small amount (~4%) of the broadband spectrum from the first stage reaches the detector as displayed in the inset at the top right of Figure 2.

The monochromatic energy can be selected by changing the material of the fluorescence target. Molybdenum, palladium, silver, and antimony generate similar monochromatic fluxes and all are potentially useful in mammography. Three of these are displayed in Figure 3. Higher energy monochromatic fluxes can be generated with target materials such as neodymium, samarium, dysprosium, tungsten and gold. The spectrum from a neodymium target is also included in Figure 3. The tube allows for easy manual exchange of the fluorescence target to select the monochromatic energy because the target is located outside the vacuum of the X-ray tube. Automated target replacement is under development. The tube technology has received a number of international patents [13-22].

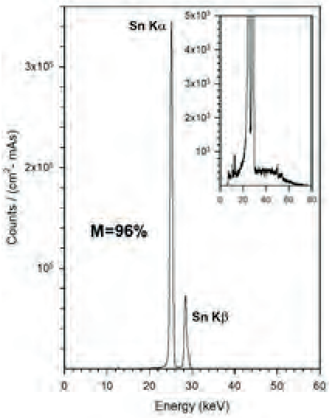

Figure 2. The fluorescence spectrum from a target of tin (Sn) emitted by the prototype is 96% monochromatic.

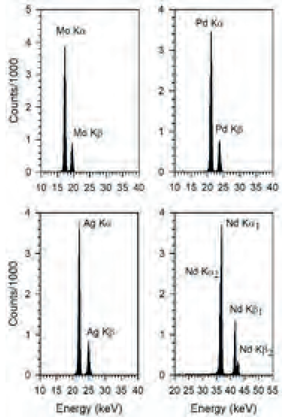

Figure 3. Additional examples of monoenergetic fluorescent X-ray lines used for imaging. Top left: molybdenum (Mo); top right: palladium (Pd); bottom left: silver (Ag); bottom right: neodymium (Nd).

IMAGING PERFORMANCE

A brief review of the imaging measurements of 4 breast phantoms with thicknesses of 4.1; 4.5; 7.1 and 9 cm reveals the image quality produced by the monochromatic system. Figure 4 shows side-by-side images from a conventional broadband mammography system (left) and the monochromatic prototype (right) of a 4.5 cm thick phantom with a 50% glandular-50% adipose equivalent tissue composition. For equal SNR (403) of the high contrast 100% glandular step wedge measured within the 5mm x 5mm black square, shown in Figure 4, the dose of the monochromatic image (0.18 mGy) is 7 times lower than that of the conventional image (1.26 mGy).

The advantage of monochromatic X-rays is even clearer for the 9 cm compressed breast phantom. The monochromatic SNR (418) was 2.6 times higher and the dose (0.65 mGy) 4.2 times lower than the respective values (158 and 2.75 mGy) obtained with the conventional system within the same 5mm x 5mm square area of the 100% glandular step wedge. For the conventional broadband system to equal the SNR of the monochromatic system, it would require a dose of 19 mGy, 29 times higher than the dose delivered by the monochromatic system.

Similar superiority in SNR and low dose are also characteristic for measurements of low contrast masses and microcalcifications. Again, comparing monochromatic and broadband imaging for equal SNRs, the conventional system requires 5 – 8 times the dose of the monochromatic system to image low contrast lesions in 4.1 cm and 7.1 cm thick phantoms. When imaging microcalcifications ranging in diameters from 400 microns to 170 microns, the dose delivered by the monochromatic system is 6.6 times lower and Figure 5 shows the comparison between the images of both technologies. It was also noted that the microcalcifications are 6 cm above the detector image plane.

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Contrast Enhanced Digital Mammography

CEDM is receiving increased attention in the screening of women at high risk of developing breast cancer and as a diagnostic tool when suspicious lesions are seen in routine screening mammograms. In addition to implementing the conventional two-image, dual energy subtraction technique commonly used with broadband systems, the recent study [7] showed how CEDM using monochromatic X-rays can be performed simply and effectively with a single image using monochromatic X-ray energies either below or above the iodine K absorption edge. The single and dual energy method used with monochromatic X-rays each has its advantages and both reduce the radiation dose compared to conventional procedures while providing high contrast and SNR. Notably, a single image acquisition typically has less statistical noise and requires less dose.

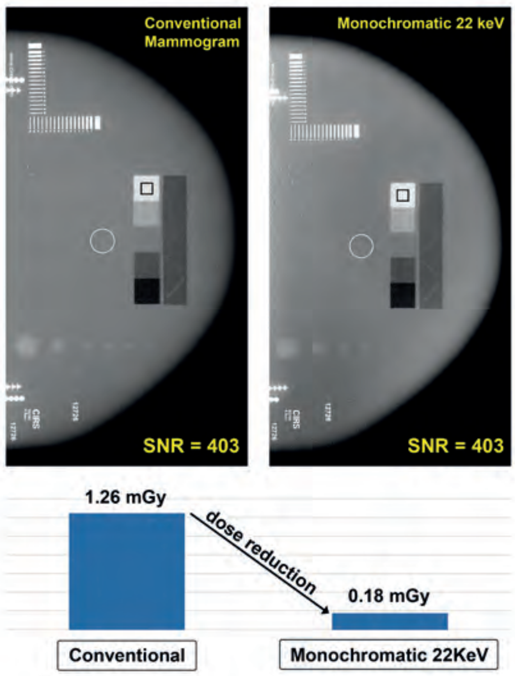

Figure 4. A 4.5cm thick breast phantom imaged with a conventional mammography unit (left) and with 22keV monochromatic X-rays from the prototype (right). The SNR for the 100% glandular step wedge is calculated for the 5mm x 5mm square outlined in black.

Using a dose of only 0.057 mGy in a single measurement, a contrast of 10% with high SNR (40) can be obtained for an iodine column density of 4.5 mg/cm^2. This means that a column

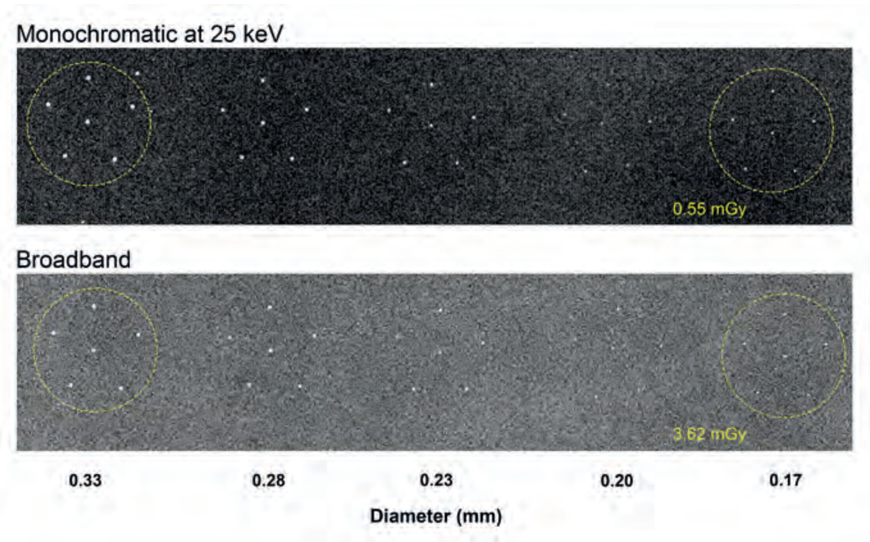

Figure 5. Images of simulated microcalcifications with diameters of 330, 280, 230, 200 and 170 microns in a 4/1 cm thick phantom for both instruments. The SNR values are equal but the dose of the monochromatic image is 6.6 time lower. The microcalcifications are 6 cm above the image plane.

density of ~0.1 mg/cm^2 could be detected with a SNR = 3 by increasing the dose to 0.65 mGy. Dual Energy subtraction using monochromatic X-rays can increase the contrast by a factor of 5 times by using a monochromatic energy below and above the iodine K-edge. This assumes that the imaging detector has a quantum efficiency of at least 85% at energies immediately above the iodine K edge. These results indicate that monochromatic X-rays enhance the potential for widespread use of CEDM while substantially reducing radiation exposure. Furthermore, single images with monochromatic X-rays could enable dynamic studies of the rate of contrast uptake by the lesion and surrounding tissue since several images can be taken in succession while still keeping the total dose at acceptable levels.

WHAT THE FUTURE HOLDS

Presently, the exposure times for the monochromatic imaging studies are relatively long, especially for imaging thick breast tissue (9 sec for 4.5 cm and 50 sec for 9 cm thick phantoms). They however serve as benchmarks for ongoing work to increase the monochromatic flux by at least 10 times, thereby reducing image acquisition time to below 5 sec on average. It is noted that current broadband mammography systems require about 17 sec to match the SNR achieved by the monochromatic prototype for the 9 cm phantom. The enhanced sensitivity adds substantial benefits and new options for screening dense and thick breasts. Screening with significantly less compression while preserving detection sensitivity is possible, thus improving patient comfort and hopefully lead to improved compliance with annual screening guidelines. When follow-up diagnostics are necessary to image small tumors or other unresolved features detected during screening, monochromatic X-rays can be used at doses approaching those currently used in breast screening by broadband mammography systems but with significantly more sensitivity. CEDM with monochromatic X-rays may be another alternative for superior diagnostic follow-up.

> *"...The enhanced sensitivity adds substantial benefits and new options for screening dense and thick breasts....."*

The factor of 5 to 10 times reduction in radiation dose per mammogram made possible by monochromatic X-rays will lead to a major reduction in total exposure from breast cancer screening and a dramatically lower risk of radiation-induced cancers in at-risk women. It is planned to carry out an initial pilot study of the technology on women by the end of this year.

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