I. Abstract.

Digital imaging systems are being introduced into the diagnostic radiology department in many areas. Digital imaging potentially offers (1) better contrast detection, (2) reduced examination time. Many digital x-ray imaging systems have now found wide spread acceptance. However digital imaging systems have not found acceptance in mammography. Mammography is the modality with the highest spatial resolution requirements in radiology. The typical limiting spatial resolution in conventional film-screen mammography is 15 lp/mm. The typical x-ray absorption is about 60 % and the Detective Quantum Efficiency (DQE) is about 30 %. It is estimated that a digital mammography system needs in excess of 2048 x 2048 pixels on a 8 x 8 " format. Digitization should be to 12 bits, and the DQE should be at least 50 % at 20 keV.

Keywords: Digital Mammography, High Spatial Resolution, Microcalcification, Low Contrast Masses, CCD, Amorphous Silicon, Fiber Optic Coupling

II. Introduction and Background

A. Digital Radiology

The diagnostic radiology department is at the beginning of a revolutionary change [1]. Digital imaging sensors and displays are under development, which may replace the traditional sensor and display, namely the film-screen combination. It is anticipated that in the not too distant future we will see the Totally Digital and Filmless Radiology Department.

The advantages of digital systems are manyfold: (1) In digital systems, the functions of image detection and image displays are separated: The images can be presented to the human observer at optimum information transfer to the observer. This should result in detection of abnormalities at an earlier stage. Furthermore the images are rarely overexposed or underexposed and rarely need to be repeated. The result would be reduced exposure to the patient. (2) The digital image can be manipulated and processed, i.e. contrast enhanced, and spatial frequency enhanced. Again improved detection at earlier stage of abnormality is expected. (3) The image is usually available faster than in the case of film: 1 to 2 sec or even 1/30 sec compared to 90 sec, resulting in reduced examination time. (4) Often the images produced by the traditional film-screen combination are limited in their contrast resolution by film noise (granularity). Avoiding the film granularity in the digital system should result in improved contrast detection.

Much progress has been made: Digital Subtraction Angiography (DSA), Computerized Axial Tomography (CAT), Diagnostic Ultrasound (US) and Magnetic Resonance Imaging (MRI) have found their firm place in the radiology Department. Recently, Computed Radiography (CR) has been introduced and
found acceptance for the demanding chest format. Unfortunately, digital imaging methods have not found acceptance in mammography. It is postulated, that none of the digital x-ray imaging systems suggested so far has the necessary spatial resolution.

It is the purpose of this paper to review the status of conventional mammography and illustrate the technical requirements for digital mammography.

B. Breast Cancer

Breast cancer is the most frequent cancer and the second leading cause of cancer related death among American women. In 1991 it is estimated there will be 175,900 new cases of breast cancer diagnosed and 44,800 breast cancer deaths will occur [2]. In all, 10-11% of all women can expect to be affected by breast cancer at some time during their lives. The cause of breast cancer is unknown, although it tends to run in families and is seen more commonly in women who never had children or who had their first pregnancy relatively late in life. Because its cause is largely unknown, there are no good preventive measures available.

Numerous studies in the last twenty years, however have shown that early detection of breast cancer can lead to a high probability for a cure [3]. Early detection therefore, is most important.

One common early sign of breast cancer is microcalcification. These calcifications appear often in clusters. The calcifications can be as small as 50 micrometer in diameter. They require the imaging system to have a very high spatial resolution. Other signs of cancer are masses exhibiting very subtle density differences with respect to the density of their surroundings, leading to contrasts of as low as 0.1 %. They require the imaging system to have a very high contrast resolution.

III. Mammography

Mammography is the science of x-ray imaging with the purpose of detecting breast cancer.

Screening mammography in combination with physical examinations the most effective means for identifying the early signs of breast cancer [4]. Only mammography can detect a small, non-palpable breast cancer.

Fig. 1 a and b are two mammograms. Fig.1 a shows an example of calcification (at the tip of the arrow), while Fig. 1 b shows a mass at the tip of the arrow.

Most of the equipment is considered dedicated [5]. The schematic in Fig. 2 a shows the components of a conventional dedicated mammography unit. They are (1) the x-ray source, (2) a compression device, (3) a scatter grid, and (4) the imaging detector, the conventional film-screen combination. The schematic in Fig. 2 b shows the components of an "ideal" digital mammography unit. Notice that the film-screen combination has been replaced by a hypothetical "flat" digital imaging panel. In this ideal system the digital sensor matches the format and approximate thickness of the conventional film/screen cassette, such that very little changes are necessary on the dedicated x-ray source.

The x-ray source typically uses a molybdenum (Mo) target and an Mo filter. With a typical voltage of 25 to 28 kVp, the x-ray spectrum predominantly consists of the characteristic x-ray lines of Mo with an effective energy of about 20 keV. This low effective x-ray energy is imperative for the generation of barely visible x-ray contrasts from the extremely low density differences.

The compression device and the scatter grid serve to preserve this contrast by removing unwanted x-ray scatter.
Fig. 1 a  Mammogram with calcification (at tip of arrow)

Fig. 1 b  Mammogram with mass (at tip of arrow)

Fig. 2 a  Schematic of conventional (film-screen) dedicated mammography unit

Fig. 2 b  Schematic of digital mammography unit using electronic flat panel
A. State-of-the-art: Mammographic Film-screen Combination

The image detector is usually a high resolution, single emulsion/single screen film-screen combination; typically its format is 8" x 10". Its limiting spatial resolution (spatial frequency at 5% MTF) is 15 lp/mm [5]. The state-of-the-art of these conventional mammographic image detectors has been described in great detail by Barnes et. al. [6], Nishikawa et.al. [7], Nishikawa et.al. [12] and Haus [5]. The result is summarized as follows for the most common one, namely the Kodak Ortho-M film and the Kodak Min-R screen:

- X-ray absorption: 58%
- Detective Quantum Efficiency (DQE): 28%
- X-ray exposure to obtain a film density of unity: 11.8 mR
- Signal-to-noise ratio for 5% contrast and 250 μm diameter object: 4.2
- Limiting resolution (5% MTF): 15 lp/mm

B. State-of-the-art: Digital Image Detectors used for Mammography

A variety of attempts have been made in the past to develop a digital imaging system for use in mammography. They include:

- Conventional screen fiber optically coupled to several CCD's (Maidment et.al. [13])
- Computed Radiography (CR, "Fuji-System" [14])

All approaches suffer from one problem or another:

- Lens coupling suffers from poor light collection, which gets worse with increasing minification.
- Fiber optic coupling exhibits significantly higher light collection than lens coupling, even though there is also a significant light loss. However, the major problem with fiber optic tapers is geometric distortion.
- CCD's are very small, the largest one known is about 2" x 2", but with only 2048 x 2048 pixels [10,11].
- Conventional x-ray image intensifiers have very poor x-ray sensitivity at 20 keV x-ray energy.
- The limiting spatial resolution (Nyquist frequency) of CR for Mammography is only 5 lp/mm

IV. Technology Constraints and Specifications: Requirements for the Digital Mammography Image Sensor

A very comprehensive study on the requirements for digital mammography was done by Chan et.al. [15]. In the absence of an ideal high resolution digital detector, they used images (mammograms) obtained with a state-of-the-art film-screen combination and digitized these films with the aid of a high resolution precision film digitizer to an array of 2032 x 2540 pixels using a pixel size (sampling aperture diameter of 0.1 mm. The contrast resolution was set to 12 bits (4096 grey levels). Subsequently they rewrote the digitized images onto film, using a laser writer with an effective beam size of 0.1 mm.
The images were then presented (together with the original images) to radiologists for the purpose of making a diagnosis. The results of the diagnosis were analyzed with the aid of ROC analysis. This analysis compares the true positive rate of detection of abnormalities with the false positive rate of detection. It was found, that the errors are significantly higher in the digitized images than in the original. It was also found that the errors could be reduced somewhat in the digitized images when image processing techniques were applied such as unsharp–masking.

The implication of this work is that a digital sensor for use in mammography has to have a pixel size smaller than 0.1 mm, and a pixel matrix larger than 2048 by 2048 for an 8 x 8 " format. At this time it is not clear for instance if a matrix size of 3000 by 3000 is sufficient.

V. Preferred Technology

In general any of the above approaches would be acceptable, provided the present limitations can be overcome. However one technology is emerging, which, if the specifications can be met, would be the preferred technology, namely the large area electronic flat panel detector, based on amorphous silicon [16], [17]. One envisions a photodiode array of an area of 8" x 8" upon which a conventional x-ray phosphor is "pressed" as the actual x-ray sensor. The light developed by the x-ray phosphor is collected and measured by the photodiodes.

Such a flat-panel x-ray detector would have the advantage to possibly fit the holder for the conventional film-screen cassette. This means that the existing dedicated radiography system does not have to be changed.

The present status is described as follows:

- Field size: 30 cm x 30 cm
- Diode pitch: 100 to 150 μm

Of particular problem is the line width for the electrodes: the lines absorb light photons, and as such, the area used for the lines is not available as sensing area. For a 30 μm line width (inter pixel spacing) and a pixel-to-pixel pitch of 100 μm about 30 % of the total array area would be covered by lines.

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