論文2003-40SC-3-9

비정질 셀레늄을 이용한 직접방식의 디지털 방사선 검출기와 X-ray film과의 MTF 측정을 통한 영상 질(Quality) 비교 평가에 관한 연구

(Comparison Study of the Modulation Transfer Function of a Prototype a-Se based Flat Panel Detector with Conventional Speed Class 400 Film/Screen System)

崔 壯 墉 *, 朴 址 君 *, 姜 相 植 *, 文 治 雄 **, 李 亨 媛 **, 南 尙 熙 **

(Jang Yong Choi, Ji Koon Park, Sang Sik Kang, Chi Woong Moon, Hyung Won Lee, and Sang Hee Nam)

요 약

디지털 방사선 검출기의 성능을 측정하기 위해 변조전달함수(Modulation Transfer Function)을 측정하여 기존 방사선 영상 시스템인 필름/스크린과 비교하였다. 제작된 디지털 방사선 검출기는 TFT 패널위에 진공 증착법을 통해 비정질 셀레늄이 코팅되었다. 비교 측정물이 감도 400의 필름/스크린은 아날로그 방식의 방사선 검출기로서 현재 임상에서 이용되고 있는 필름이다. Square wave & slit 측정법을 통해 두 시스템의 변조전달함수를 측정하였다. 필름/스크린의 반치폭(FWHM)은 357㎛(1.4 lp/mm at 50% spatial frequency)으로 측정되었으며, 디지털 방사선 검출 시스템은 200㎛(2.5 lp/mm at 50%)였다. 영상의 표현 성능 평가의 결과 디지털 방사선 시스템은 필름 시스템보다 높은 것으로 나타났다.

Abstract

To evaluate the performance of the digital radiography(DR) system developed in our group, the modulation transfer function(MTF) was measured and compared with that of an analog X-ray detector, film/screen system. The DR system has an amorphous selenium(a-Se) layer vacuum-evaporated on a TFT flat panel detector. The speed class 400 film/screen(Fuji) system has been being used in the clinical field as analog X-ray detectors. Both the square wave and slit method were used to evaluate their MTF. The square method was applied to both film/screen and the DR system. The slit method, however, was applied to only DR system. The full-width half maximum resolution of film/screen was 357㎛(1.4 lp/mm at 50% spatial frequency), and the resolution of DR was limited to 200㎛(2.5 lp/mm at 50%). These results indicate the measured resolution limitations approximate to the pixel pitch, 139 ㎛, of TFT. The MTF of DR is higher than that of film/screen by the factor of 1.785. It is proved that our a-Se based DR system has potential usefulness in the clinical field.

Keyword : Digital Radiography, Modulation Transfer Function, Resolution, Spatial-Frequency

---

* 正會員, 仁濟大學校 醫用工學科 放射線映像硏究室
(Radiation Image Lab. Department of Biomedical Engineering, Inje University)
** 正會員, 仁濟大學校 醫料映像硏究所
(Medical Image Research center, Inje University)

※ This work was supported by National Research Laboratory program (M1-0104-00-0149)
接受日字:2002年9月23日, 수정완료일:2003年4月7日

I. Introduction

Film/screen has been used to acquire the conventional radiographic examinations by capturing the pattern of x-rays transmitted through a patient. Recently, however, with their advent, active matrix flat-panel imagers are beginning to replace the sheets of film. These detectors use either the indirect or the direct method to detect x-ray[1]. Indirect detectors convert x-rays to visible light at the scintillating layer. This visible light is again converted to electron-hole pairs within a photo-conductive layer. After that, the electrical signal is acquired by the readout component of the imaging system. On the other hand, a direct detector directly converts x-rays to electric charges within a photo-conductive layer[2, 3]. Amorphous selenium (a-Se) usually has been used for this photo-conductive material. The demand for DR systems is increasing because it is expected to solve some problems of analog radiographic systems such as the exhaustion of storage space, film management, and environmental pollution. It is also well known that the direct radiography system has a higher spatial resolution than an indirect imager.

A direct a-Se based flat panel x-ray detector has been developed for the first time in Korea. Several quantitative parameters have been devised that correlate with the abilities of imaging devices to perform clinical tasks. Such parameters can be employed both for intercomparison between systems and for quality control of a particular system over time. One of the most widely used of these is the modulation transfer function(MTF), a measure of how well a system handles contrast and different levels of fine detail[4]. The function, MTF(f), is thus a measure of the ability of the imaging system to handle contrast as a function of spatial frequency. In this study, therefore, MTFs of our DR detector and a film/screen system were compared to evaluate their abilities to handle contrast and different levels of fine detail as a function of spatial frequency.

II. Measurements of Modulation Transfer Function

The modulation, M, of any periodic signal, Ψ, is defined by the following equation[5]:

$$M = \frac{\Psi_{\max} - \Psi_{\min}}{\Psi_{\max} + \Psi_{\min}} \tag{1}$$

Ψ_{max} : The signal intensity from background to the highest peak

Ψ_{min} : The signal intensity from background to the lowest peak

That is, the modulation refers to the contrast, relative to its background or average value, of a periodically varying signal. Suppose the input to the device is a signal of frequency f and modulation Min(f), and the value of the modulated output signal, Mout(f). The modulation transfer function, MTF(f), is the function that records the modulation transfer ratio for all frequencies[6-8]:

$$MTF(f) = \frac{|M_{out}(f)|}{|M_{in}(f)|} \tag{2}$$

If Min(f) = 1.0 as the Fourier amplitude of the response to a delta-function input to the system,

$$MTF(f) = |M_{out}(f)| = |OTF(f)| \tag{3}$$

where OTF(f) is the optical transfer function, the Fourier transform(FT) of the point spread function (PSF).

In this study, MTFs were measured by two methods, one was the square wave method and the other was the slit method.

1. Square wave Method

This method uses a bar pattern with progressively narrower patterns of dark and light to determine the approximate frequency response of a system. The pixel values behind the bar pattern are then analyzed to determine the amplitude of response at each of the discrete frequencies included in the bar pattern. This amplitude reflects the square wave response of the system, not the response to a sinusoid. Thus it is not directly a measure of the MTF. It may be converted to a sinusoid response by using the following approximate formula :

$$MTF(f) = \frac{\pi}{4}[MTF_s(f) + \frac{1}{3}MTF_s(3f) - MTF_s(5f) + \cdots] \quad (4)$$

where MTF(f) is the sinusoidal response at spatial frequency u and MTFs(f) is the square wave transfer function derived from the bar pattern[9].

2. Slit Method

The "overall" two dimensional MTF in the digital system can be expressed by Eq. 5

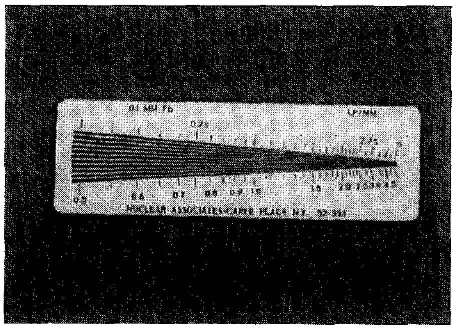
$$MTF(u, v) = [MTF_S(u, v)] * \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \delta(u - m/\Delta x, v - n/\Delta y) \quad (5)$$

where MTFS is a sampling aperture and * denotes the operator of convolution. The factor m and n are integers, and Δx and Δy are sampling distances in x and y directions, respectively. Sampling distance Δx and Δy should be shorter than the pixel pitch of the detector in order to eliminate the aliasing effect. The slit method measures the response to an impulse function, but rather than a delta function, it uses a slit. The system response, therefore, is given by the convolution of the PSF with the slit and this results in the line spread function (LSF). A slit is placed at a shallow angle with respect to the pixel matrix to measure the LSF. The LSF is synthesized as a plot of pixel value versus distance from the slit. In order to promote consistency in measuring LSFs with very long tails, extrapolation was performed beyond the point where the LSF was measured. Presampling MTF was calculated from extrapolated LSF by performing fourier transform. After that, the resulting values were normalized. MTF including effective sampling distance was obtained by performing the convolution with presampling MTF and comb function as shown in Eq. 5.

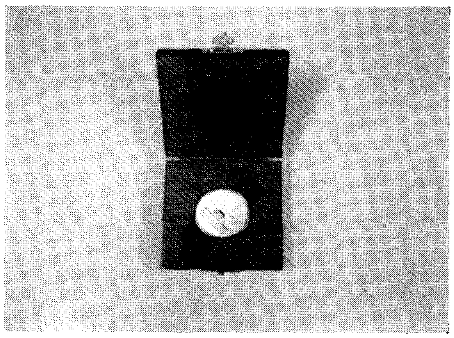
Ⅲ. Method

1. Radiographic Imaging

All X-ray exposures were acquired using the Toshiba DRX-353570 system[Japan]. Identical radiographic technique factors were used for both DR and film/screen images wherever possible. These exposure conditions were 100mA, 44kVp, 0.05 sec. A line-pair phantom[Nuclear Associates, N.Y., U.S.A., 07-523] and micro-slit-camera[Nuclear Associate, N.Y., U.S.A., 07-512] were used as imaging objects. The line-pair phantom has 100 ㎛ thick lead bars with progressively narrower patterns as shown in <Fig. 1(a)>. This phantom was used to measure the square wave transfer function. And the micro-



(a) Line-pair phantom



(b) Micro-slit-camera

그림 1. 해상도 및 마이크로 슬릿 팬텀
Fig. 1. Photography of line-pair phantom and micro-slit-camera.

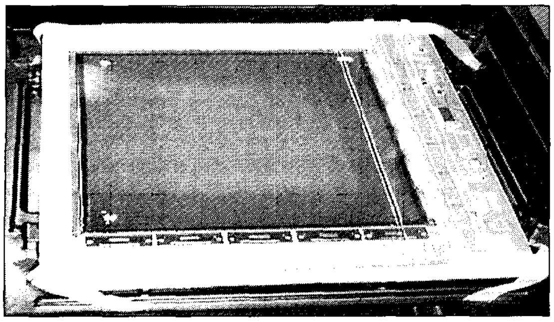


그림 2. 비정질 셀레늄을 이용한 디지털 방사선 검출기 원형 시스템

Fig. 2. Digital radiograph detector Prototype using a-Se.

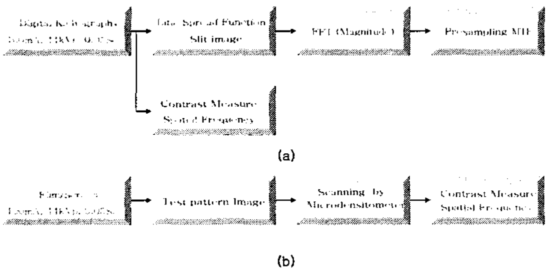


그림 3. 디지털 방사선 시스템 및 필름 시스템의 변조 전달함수 평가 순서도

Fig. 3. Schematic diagrams of work flow for measuring MTF of (a) digital radiography system and (b) film/screen systems.

slit-camera shown in <Fig. 1(b)> has a narrow slit with 10 ㎛ slit width. The LSF of the DR system was obtained with this slit camera. Conventional X-ray image was obtained using Rare-earth screen/film [Fuji medical, Japan] and digital X-ray image was acquired using a-Se based DR detector system with TFT flat panel developed in our group.

Modulation transfer function of the DR system was compared with the features represented in a film/screen system[10, 11]. The schematic work flow diagrams for measuring MTF of the digital radiography system and the film/screen system were depicted in <Fig. 3>. As shown in this figure, MTF of the a-Se based DR detector was measured using two methods, square wave method and slit method, but MTF of the conventional film/screen system was acquired only by the square wave method. Gray level of the film/screen image was converted to digital value using a microdensitometer(2020 GMS, USA). Gray level of the DR system was directly extracted from digital pixel values.

2. Film/screen system

The spatial resolution limit of the DR system was compared with that of the Fuji medical rare-earth film/screen image. The manufacturer reports this screen-film combination as having a nominal speed of 400. The digital intensity values of the sample points on the x-ray phantom image of film/screen were acquired using microdensitometer with 12-bit ADC and a sampling distance of 5㎛. Thirteen discrete spatial frequencies in the normal diagnostic range of 0.5~4.0 lp/mm was selected from the pixel values behind the bar pattern of the line-pair phantom image. The spatial frequencies of the line pattern were determined by the division of the scale marked with lp/mm on the phantom<Fig. 4> and they were selected at 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.3, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 lp/mm, respectively. The square wave transfer function MTFs(f) was interpreted by examining the pixel intensity profile of the phantom image in the perpendicular direction of the bar pattern. And then the modulation transfer function MTF(f) was derived from MTFs(f) using equation[5].

3. Digital Radiography using a-Se

The Digital radiography system shown in <Fig. 2> uses a flat panel array detector that an a-Se layer covers on the top of the TFT panel by vacuum vaporization. The size of this detector system which is consist of 1536×1280 matrix was 8.5×7.0 inch2 with 139㎛ of horizontal/vertical pitch and its optical fill factor is more than 80%. These factors theoretically correspond to the limiting spatial resolution of 3.6 lp/mm. The a-Se layer has an estimated thickness of ~500 ㎛. At a photon energy of 40 keV, x-ray absorption at this layer will be close to 100%. Both the square wave and slit method are used to access the MTF presenting the limiting spatial resolution of the DR detector.

(1) Square wave method

The MTF of the DR system was examined using the same method as in the film/screen case except that the pixel values are directly read from digital images without using a microdensitometer. <Fig. 4> shows an x-ray image of the line-pair phantom acquired from the a-Se based DR system.

(2) Slit Method

This method uses a Micro-slit-camera [Nuclear Associate 07-512] which has very a thin slit width of 10μm placed at a slanted angle with respect to the pixel matrix to measure the LSF at a sampling interval much finer than that provided by the pixel-to-pixel distance. It could eliminate an aliasing effect produced by discrete data sampling. <Fig. 5> shows the X-ray image obtained by slanted aligning of the slit camera with a shallow angle to the pixel line of the DR detector system[12]. Pixel values in the vicinity of the angled slit represent samplings of the LSF at distances equal to the length from the slit center to the pixel center. The LSF is computed by plotting the image intensity versus distance from the center of the slit for each pixel in a region of interest surrounding the slit. It is necessary to fill in any missing values and resample the LSF so that an identical spacing is used between all points. Fig. 6 shows a composite LSF obtained by combining several intensity profiles of slit in image. Finally, the presampled MTF was achieved by performing the fourier transform function from the composite LSF.

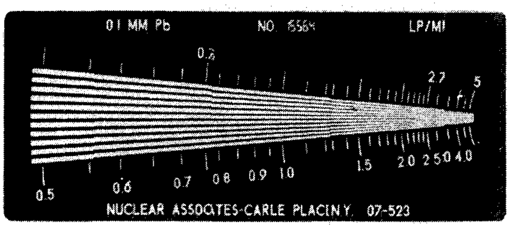


그림 4. 디지털 방사선 검출 시스템을 이용하여 획득한 해상도 팬텀 영상

Fig. 4. Line-pair phantom image of a-Se based DR system.

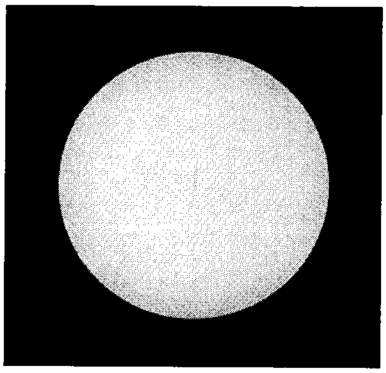


그림 5. 디지털 방사선 검출 시스템을 이용하여 획득한 마이크로슬릿 팬텀 영상

Fig. 5. Micro-slit x-ray image of slanted slit phantom.

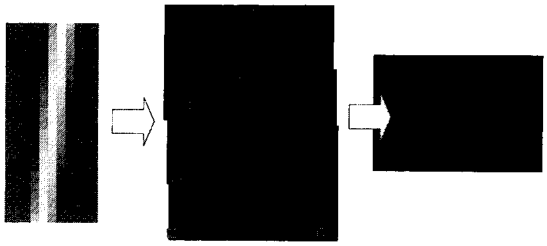


그림 6. 기울인 마이크로 슬릿 이미지의 확대영상의 라인 분포 영상

Fig. 6. Magnified micro-slit x-ray image and LSF obta- ined from several different intensity profile of inclined slit.

Ⅳ. Results and Discussion

1. MTF of Film/Screen System

<Fig. 7> shows four intensity profiles of thirteen line measured by microdensitometer on the film image at the positions of 0.5, 1.0, 1.5 and 2.5 lp/mm. All modulation values at each spatial frequency calculated from these intensity profiles. Graphical presentation of these modulation values are illustrated in <Fig. 8> as an MTF(f) of film/screen system in the range of spatial frequency from 0.5 to 4.0 lp/mm. Since the input modulation function, Min(f), comes from the real object, line-pair phantom, Min(f) equals 100% for all spatial frequencies. From equation 3, MTF(f), therefore, becomes equivalent to Mout(f) in

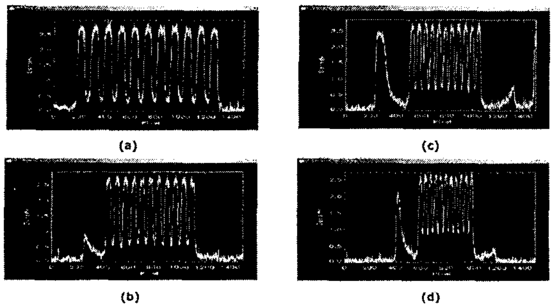


그림 7. 0.5, 1.0, 1.5, 2.0 lp/mm에서 마이크로 덴시토 미터로 측정된 film의 강도 분포 영상

Fig. 7. Film intensity profiles measured at (a) 0.5, (b) 1.0, (c) 1.5 and (d) 2.5 lp/mm on line-pair phantom images by microdensitometer.

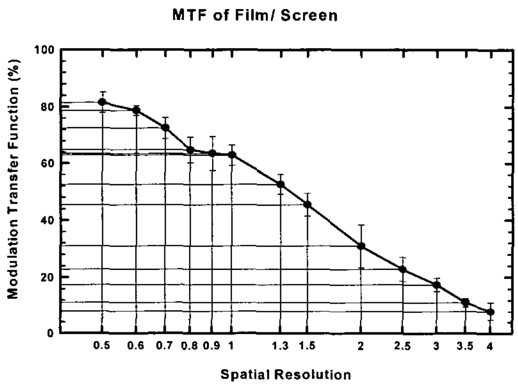


그림 8. 필름의 MTF 특성 곡선

Fig. 8. Graphical presentation of the measured MTF in Screen/Film system.

this study. This result shows that increasing spatial frequency causes reducing differences between maximum and minimum intensities, therefore, the output modulation function, MTF(f), is decreased. Full width half maximum(FWHM) value of the modulation transfer function for the screen-film combination was about 1.37 line pairs per mm. This value is close to the value, about 1.6, normally expected for a 400 speed screen-film combination.

2. Digital Radiography using a-Se

(1) Square wave method

Four intensity profiles of the line-pair phantom image obtained by the DR imaging system were directly read in digital format at 13 positions marked

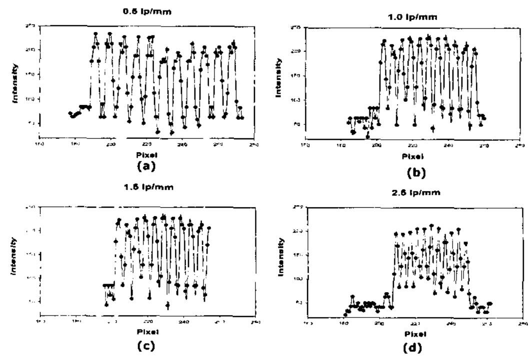


그림 9. 0.5, 1.0, 1.5, 2.0 lp/mm에서 마이크로 덴시토 미터로 측정된 디지털 시스템의 강도 분포 영상

Fig. 9. Intensity profiles measured at (a) 0.5, (b) 1.0, (c) 1.5 and (d) 2.5 lp/mm on line-pair phantom digital image.

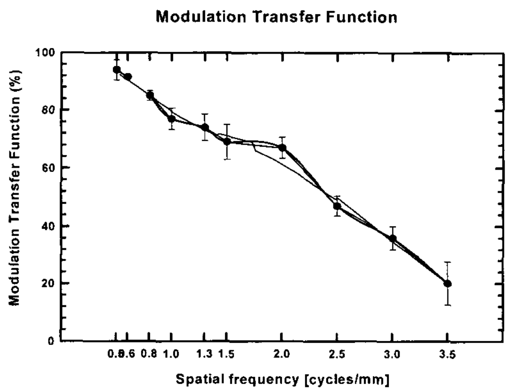


그림 10. 디지털 검출시스템의 MTF 특성 곡선

Fig. 10. Graphical representation of MTF of a-Se based DR system obtained by contrast method.

with spatial frequencies of 0.5, 1.0, 1.5, and 2.5 lp/mm. All modulation values of these intensity profiles at each spatial frequency were calculated using equation 1.

<Fig. 10> shows the MTF curve obtained by use of the same method as in the film/screen experiment. From the intensity profile of the x-ray line-pair phantom image, modulation was 36% at 3.0 lp/mm. The resolution limitation of an a-Se based DR system calculated from this MTF curve was about 2.6 line pairs per mm at FWHM.

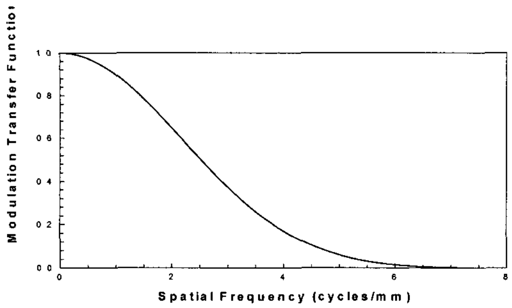


그림 11. 슬릿을 이용하여 획득한 디지털 검출시스템의 프리 샘플링 MTF
Fig. 11. Presmapled MTF in DR system obtained by slit method.

(2) Slit Method

The presampled MTF curve shown in <Fig. 11> was obtained from a finite composite LSF at 3 lp/mm~6 lp/mm using Fourier transform. The extrapolating operation was applied to 0.01% of the maximum value of the LSF curve. Percent modulation values were 78% and 38% at the spatial frequencies of 1 lp/mm and 3 lp/mm, respectively. The resolution limitation of the DR system calculated from the MTF(f) curve of <Fig. 11> was 2.3 lp/mm and this result is less than the result of the square wave method.

V. Conclusion

This study evaluates the MTF of the DR system by comparing it with that of a film/screen system to confirm the performance of amorphous-selenium based DR systems in the clinical field. Compared to film/screen systems being used in conventional radiography. For this comparing, the conventional radiography was converted to the digital signal by using microdensitometer which has 1um resolution of location precision. This resolution is enough for comparing two systems. The DR system has somewhat higher MTF and shows better contrast in the same exposure conditions. Thus, a reduced x-ray exposure can be expected in DR system. Also film imaging systems have a characteristic curve that is linear ,with respect to logarithm of incident intensity, over about 1 to 2 orders of magnitude. But DR shows an excellent image contrast over a wide latitude of x-ray exposure. DR system measure their characteristic response directly with respect to exposure rather than the log of exposure as with film, and typically have a range of linear response of 3 to 4 orders of magnitude. In fact, the influence of noise on the MTF results obtained in this study has not been considered. To calculate the MTF, however, the peak intensity of the line profile for the MTF measurement must be averaged. In conclusion, we compared the performance of the two x-ray imaging devices, the conventional film/screen detector and the digital radiograph system, by determining MTF. The MTF of the DR system was superior to that of film/screen. Presampling the MTF exposed the characteristics of unsharpness and the sampling aperture of the detector. At a cutoff frequency of 3.5 lp/mm, the MTF was measured as 11% for the film/screen system, 20% for the contrast method of the DR system and 27% for the slit method of the DR system. This results shows the potential usefulness of the DR system using amorphous selenium in clinical work. But this is not enough for evaluating the DR system performance. Continuously we have to evaluate the noise power spectrum and detective quantum efficiency for more precise performance evaluation of the DR system.

참 고 문 헌

[1] A.R. Cowen, "Digital X-Ray Imaging." Meas Sci Technol., Vol. 2, pp. 691~707, 1991.

[2] W. Zhao, J.A. Rowlands, "X-Ray Imaging Using Amorphous Selenium: Feasibility of a Flat Panel Self-Scanned Detector for Digital Radiology." Med. Phys. pp. 1595~1604, May. 1995.

[3] M. J. Yaffe, J. A. Rowlands. "X-ray detectors for digital radiography." Med. Phys. pp. 1~39, Nov. 1977.

[4] L. Denny, Y. Lawrence, K. Cheung, Palecki,

and Lothar S. Jeromin. "A Discussion on Resolution and Dynamic Range of Se-TFT Direct Digital Radiographic Detectors." SPIE Physics of Medical Imaging, pp. 254~263, 1996.

[5] A. B. Wolbarst, G. Cook, Physics of Radiology, Appleton & Lange, 1993.

[6] Glenn D. Boreman, Modulation Transfer Function in Optics and Electro-Optical System SPIE Press, Washington USA, 2001.

[7] J. F. Veenland And J. L. Grashuis, "Texture Analysis in Radiographs : The Influence Of Modulation Transfer Function And Noise On The Discriminative Ability Of Texture Features," Med. Phys. pp. 453~466, June. 1988.

[8] W. Zhao And J. A. Rowlands. "Digital Radiology Using Active Matrix Readout Of Amorphous Selenium: Theoretical Analysis Of Detective Quantum Efficiency," Med. Phys. Sep. 1988.

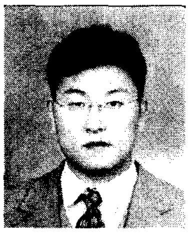
[9] J. Beutel, J. M. Fitzpatrick and S. C. Horii, et. al., Handbook of Medical Imaging, SPIE PRESS, Washington, 2000.

[10] M. A. Ferrari, A. Pilot, G. Manuzio, S. Squarcia and LE Derchi. "Overall image quality comparison between a digital X-ray detector (DirectRay) and conventional screen-film systems." ECR , March. 1999.

[11] S. Gary, A. Maidment, J. Bell, L. Jeromin, and G. Powell. "Full Field Digital Projection Radiography System : Principles and Image Evaluation." Computer Assisted Radiology and Surgery (CAR '97), pp. 39~45, 1997.

[12] Hiroshi Fujita, Du-Yih Tsai, Takumi Itoh Kunio Doi, "A Simple Method for Determining the Modulation Transfer Function in Digital Radiography", IEEE Transactions on Medical Imaging, Vol. 11, NO. 1, Mar 1992.

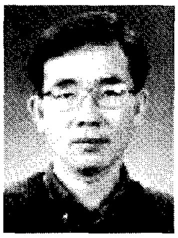
저 자 소 개



崔 壯 墉(正會員)
INJE University 2000, B.S. in Biomedical Engineering, INJE University 2002 M.S. in Biomedical Engineering, INJE University 2002 Ph.D. course, in Biomedical Engineering, <Special Study : Image quality evaluation of Digital radiography system>

朴 址 君(正會員)
INJE University 1999, B.S. in Biomedical Engineering, INJE University 2001 M.S. in Biomedical Engineering, INJE University 2003 Ph.D. in Biomedical Engineering, <Special Study : Radiation Physics>

姜 相 植(正會員)
INJE University 2000, B.S. in Biomedical Engineering, INJE University 2002 M.S. in Biomedical Engineering, INJE University 2002 Ph.D. course, in Biomedical Engineering, <Special Study : Radiation sensor coating>



文 治 雄(正會員)
Sogang University, 1983, B.S. in Electrical Engineering, Advanced Institute of Science and Technology, 1985, M.S. in Electrical Engineering, Advanced Institute of Science and Technology, 1991, Ph.D. in Electrical Engineering, Human-science in A-san hospital, 1991~1995, Samsung Advanced Institute of Technology 1996~1999, Assistant Professor : Inje University in Dept of Biomedical Engineering, 1999~present ---> 논문 제 39권 SP편 제5호를 참조 부탁드립니다.
<Special Study: Magnetic Resonance Imaging(MRI), System Signal & Image System>

李 亨 媛(正會員)

Sogang University, 1983, B.S. in Physics, Sogang University, 1985, M.S. in Physics, Sogang University, 1989, PhD. in Physics, Post Doctor : University of Rome and ICRA, 1989.3~1993.2, Assistant Professor : Inje University in Dept of Physics, 1993.3~1998.3, Associate Professor : Inje University in Dept of Physics, 1998.4~present <Special Study : Big Bang Nucleosynthesis,Quantum Gravity and Black Hole, Nonlinear and Chaos>

南 尙 熙(正會員)

Young-Nam University, 1978, B.S. in Physics, Young-Nam University, 1980, M.S. in Physics, Young-Nam University 1988 Ph.D. in Physics, Medical Researcher in Seoul National University college of medicine 1997~2003, Professor : Inje University in Dept of Biomedical Engineering 2002 - present <Special Study : Digital Radiography (detector, material science)>