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<원저>

Evaluation of Image Quality for Various Electronic Portal Imaging Devices in Radiation Therapy*

- 방사선치료의 다양한 EPID 영상 질평가 -

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— Abstract —

In megavoltage (MV) radiotherapy, delivering the dose to the target volume is important while protecting the surrounding normal tissue. The purpose of this study was to evaluate the modulation transfer function (MTF), the noise power spectrum (NPS), and the detective quantum efficiency (DQE) using an edge block in megavoltage X-ray imaging (MVI).

We used an edge block, which consists of tungsten with dimensions of 19 (thickness) × 10 (length) × 1 (width) cm^3 and measured the pre-sampling MTF at 6 MV energy. Various radiation therapy (RT) devices such as TrueBeam™ (Varian), BEAMVIEW^{PLUS} (Siemens), iViewGT (Elekta) and Clinac®iX (Varian) were used. As for MTF results, TrueBeam™(Varian) flattening filter free(FFF) showed the highest values of 0.46 mm^{-1}and1.40mm^{-1}for MTF 0.5 and 0.1. In NPS, iViewGT (Elekta) showed the lowest noise distribution. In DQE, iViewGT (Elekta) showed the best efficiency at a peak DQE and 1 mm^{-1}DQE of 0.0026 and 0.00014, respectively.

This study could be used not only for traditional QA imaging but also for quantitative MTF, NPS, and DQE measurement for development of an electronic portal imaging device (EPID).

Key Words: Modulation transfer function (MTF), Noise power spectrum (NPS), Detective quantum efficiency (DQE), Electronic portal imaging device (EPID)

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Ⅰ. INTRODUCTION

Digital radiography (DR) is a common worldwide technology and has gained popularity in megavoltage X-ray imaging (MVI)[1]. In the last few years, other digital technologies, most notably the solid-state-based flat-panel detector technology, have gained popularity[2]. The terbium-doped gadolinium-oxysulfide granular phosphor (Gd_2O_2S:Tb) screen is the most popular X-ray converter. In addition, the Gd_2O_2S:Tb screen is very cost-effective, because of its easy technical handling, thickness, bulkiness and flexibility[3,4]. In Megavoltage (MV) radiotherapy, delivering the dose to the target volume is important while protecting the surrounding normal tissue. The verification of patient alignment in radiotherapy is necessary to ensure that a high dose is delivered to the tumor while the healthy tissue is spared. Portal imaging is one of the most frequently used tools for such verification. Discrepancies in field placement frequently occur and they can influence the outcome of a treatment[5,6]. With the increase of verification, localization errors are decreased[7,8]. The measurement used to evaluate the fundamental performance of imaging systems is the modulation transfer function (MTF), which describes the signal transfer characteristics of the system as a function of spatial frequency. An accurately measured MTF is used to describe the imaging performance of the overall radiograph and it is essential to decide the detective quantum efficiency (DQE) of the imaging device[9]. The noise power spectrum (NPS) is one of the most common methods regarding the measurements of the noise and the quality of the image acquired with a uniform radiation field[10]. Various performance methods based on bar patterns, slits and edges have been suggested to calculate the pre-sampled MTF of the digital radiograph system[11-17]. Edge methods are generally used and preferred for various reasons, including their having a simple construction and less sensitivity with respect to misalignment. Therefore, methods to determine the edge method are acceptable for MTF measurements. Imaging devices designed for radiotherapy should meet the requirements concerning the position and the dose verification at the same time. To be profitable they ought to be used in daily routine to quickly check the patients' alignment as well as the dose and to allow a quick correction if it is necessary[18].

The purpose of this study was to evaluate the MTF, the NPS, and the DQE using an edge block in electronic portal imaging device (EPID) and meet the requirements concerning the position and the dose verification at the same time.

Ⅱ. MATERIALS AND METHODS

1. Edge Block

We made an edge block, which consists of tungsten with dimensions of 19 (thickness) × 10 (length) × 1 (width) cm^3 and has a density of 19.3 g/cm^3, higher than steel (~7.9 g/cm^3). In order to obtain MTF measurements, the focus and size of 3 mm and 1 monitor unit (MU) MV X-ray (according to calibration established by our clinic for this linear accelerator (LINAC), 1 MU corresponds to a dose of 0.8 cGy deposited in water at a source-to-detector distance equal to 100 cm, with 10 cm overlying water, for a field size of 10 × 10 cm^2 at the iso-center, i.e., at 100 cm.) should be restricted and the source must be perpendicular to the edge boundary's surface center (Figure 1).

2. The X-ray Imaging System

For the measurements, we used four DR MVI systems which are clinically used. In DR MVI systems, a first-generation lens-coupled video electronic EPID BEAMVIEW^{PLUS} (Siemens), an indirect detection a-Si flat-panel EPID iViewGT (Elekta) and an aS1000 (Varian) which set up as Clinac® iX and TrueBeam™ (Varian) were used. EPID systems use phosphor screens (Lanex Fast-Back) and they are indirect types of detectors that have fundamental modes due to the Gd_2O_2S:Tb granular phosphor material or CsI fluorescence[19]. The BEAMVIEW^{PLUS} is set up as a PRIMUS Linac, which has a phosphor detector combined with a mirror and the lens of a camera system, and the source−detector distance (SDD) is 132 cm. Elekta iviewGT has a 41 × 41 cm^2 sensitive area, and a 1024 × 1280 photodiode array, and it is set up as precise Linac (Elekta). The aS1000 of Clinac® iX (Varian) is set up to operate in a stand−alone configuration so that the Varian aS1000 can be used independently from the clinical imaging on the treatment unit. The imaging panel (IDU 20) includes a 1−mm Cu build up plate, a Gd_2O_2S:Tb scintillating phosphor layer, and a 1024 × 768 array of photodiodes switched by thin−film transistors deposited on a glass substrate. The pixel dimension is 0.39 mm and the panel has a sensitive area of 40 × 30 cm^2. The TrueBeam™ (Varian) Portal Vision imager has an imaging area of 40 × 30 cm^2 at a SDD and an array of 1024 × 768 pixels. The performance evaluation of Varian TrueBeam™ was performed as flattening filter and flattening filter free. The SDD of the four DR devices are 132 cm. In all MVI units, a change is caused by magnification because the edge block is projected to be close to the minimum iso−center. Thus, the magnified dose distribution is not uniform. Table 1 lists the characteristics of the DR detectors used in our study.

3. Measurements

The MTF measurement was performed using the pre−sampled MTF method described by Fujita et al.[12, 20−22]. The MTF describes the resolution of the detector. The MTF was measured using the slant−edge (2~3°) method to avoid aliasing because of the relatively large sampling interval of the detector. The exact angle of the edge line in the region of interest (ROI) was determined by a least−square fit to the edge transition data. The acquired edge spread function (ESF) was differentiated to obtain the line spread function (LSF). The MTF in the direction perpendicular to the original edge line was computed by performing a fast Fourier transfer (FFT) of the LSF and normalizing its value to unity at a zero spatial frequency.

The NPS as function of spatial frequency measures the variations in the noise amplitude, and it describes the noise and spatial frequency properties within the image. The method for computing the NPS, spectrum, as it is used in our quality assurance (QA) algorithm can be described by using recommendations by the IEC 62220−1 for the standardization of NPS[10]. In order to assess the NPS, white images are obtained by projecting onto detectors without an object. Then, 1024 × 512 2D white images were used and each NPS data was calculated. We applied two−dimensional FFTs in order to obtain ROI images and we performed a scale revision using the average ROI extracted from the whole image. The matrix size was 1024 × 512 pixels, the pixel size was 0.172 × 0.172 mm^2, and the field of view was 17.6 × 8.80 cm^2. Image preprocessing as applied in normal clinical use of the detector consists of offset and gain corrections, as well as compensation for defective or nonlinear pixels. A pixel is a bit depth of 16 bits. Image data were acquired the central area of each image by overlapping from a 256 × 256 ROI size with a pixel sampling pitch of 0.172 mm and from image sections with 21 ROI slices.

Table 1 DR configurations for portal localization

Imaging systems	Detector type	Detector material	Array size	Imaging area
Siemens BEAMVIEWPLUS	Indirect	a-Silicon	1024 × 1024	41 × 41, 24 × 31 at isocenter
Elekta iViewGT	Indirect	a-Silicon	1024 × 1280	41 × 41, 26 × 26 at isocenter
Varian Clinac® iX	Indirect	a-Silicon	1024 × 768	40 × 30 at isocenter
Varian TrueBeamTM	Indirect	a-Silicon	1024 × 768	40 × 30 at isocenter

DQE was calculated using MTF, normalized NPS (NNPS), and the following equation (1).

$$DQE(f) = \frac{MTF^2(f)}{q \times NNPS(f)} \qquad (1)$$

In equation (1), MTF^2 (f) is the MTF that depends on the frequency, NPS is that depends on the frequency and NNPS (f) is the normalized NPS that depends on the frequency and q is the number of X-ray photons. We used based on monte carlo simulation (MC) photon fluence (photons/mm^2). The DQE can be evaluated from the measured MTF and NPS.

Ⅲ. RESULTS

1. Detector Response

Digital image communication of medicine (DICOM) images were then acquired, and gain and defective pixels were applied with standard corrections for X-ray heel effect and detector offset. Linear measurement is not affected by bad pixel and gain corrections. DR systems such as Varian TrueBeam^{TM} flattening filter, Varian TrueBeam^{TM} FFF, Varian Clinac$^{®}$ iX aS1000, Siemens BEAMVIEW^{PLUS} and Elekta iviewGT respectively indicated the following values: 0.9967, 0.9975, 0.9980, 0.9975 and 0.9975. In Figure 2, The R^2 value close to 1 shows the stabilized linearity of the system. The results

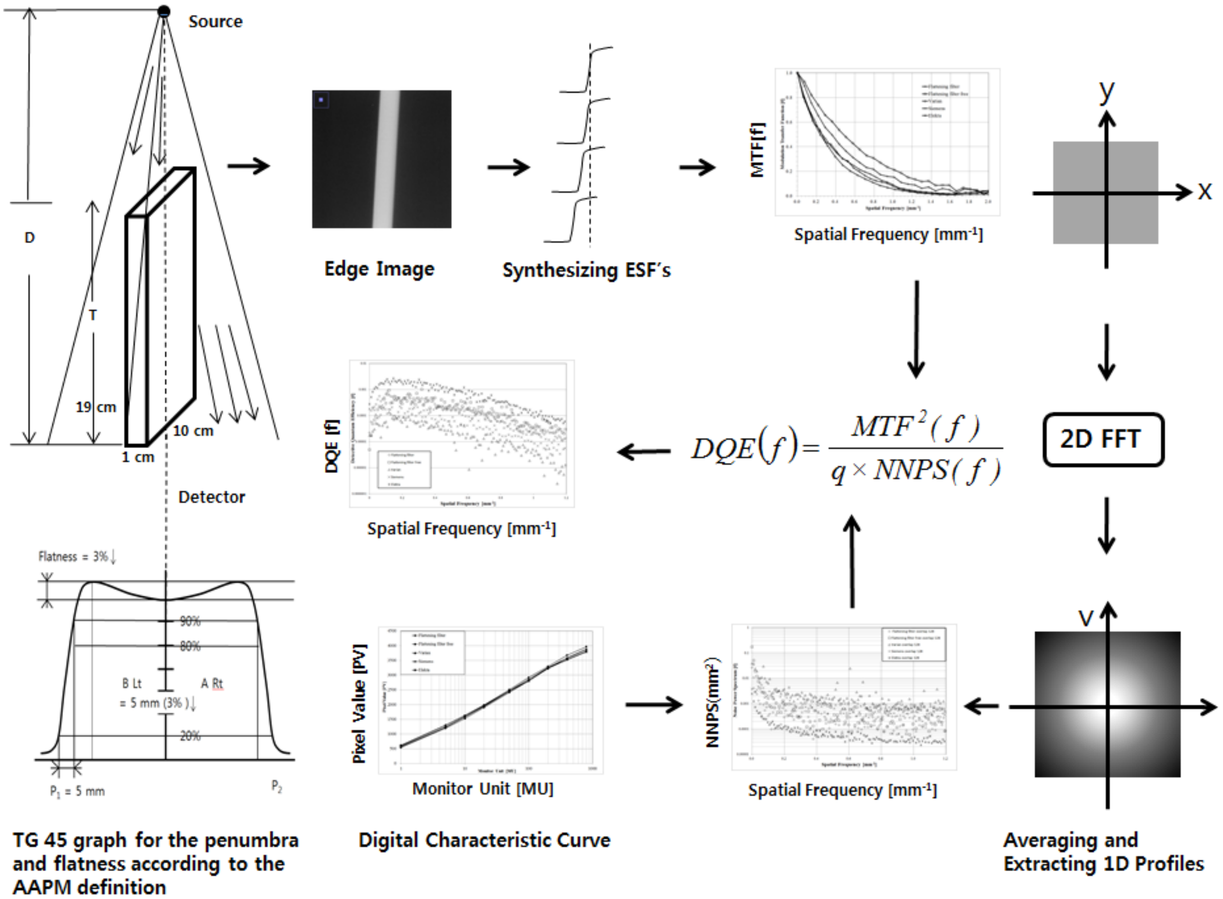

Figure 1 TG 45 graph for the penumbra and flatness according to the AAPM definition. The MTF was computed by performing a fast Fourier transfer (FFT) of the LSF and normalizing its value to unity at a zero spatial frequency. The one-dimensional NPS was expressed by averaging the axis direction from the bandwidth of the two dimensional NPS space, and the accumulation correction was calculated by extracted the ROI from the whole image size. The DQE was evaluated from the measured MTF and NPS

showed the linearity for MTF measurements in our experiments.

2. Modulation Transfer Function (MTF)

As for the MTF edge method, because ESF, LSF, and the windowing function affect the results, we used the standard method. Table 2 shows the spatial frequencies for 10% and 50% of the pre-sampling MTFs. The DR systems used in study were Siemens BEAMVIEW^{PLUS}, Elekta iViewGT, Varian TrueBeam^{TM} and Varian Clinac® iX aS1000, which are a-Si flat panel detectors.

The spatial frequencies corresponding to 50% of MTF for Varian TrueBeam^{TM} flattening filter free (FFF), Varian TrueBeam^{TM} flattening filter, Siemens BEAMVIEW^{PLUS}, Elekta iViewGT, and Varian Clinac® iX aS1000 were 0.46, 0.37, 0.26, 0.26 and 0.23 mm^{-1}, respectively (Figure 3). The spatial frequencies corresponding to the 10% of MTF for Varian TrueBeam^{TM} FFF, Varian TrueBeam^{TM} flattening filter, Siemens BEAMVIEW^{PLUS}, Elekta

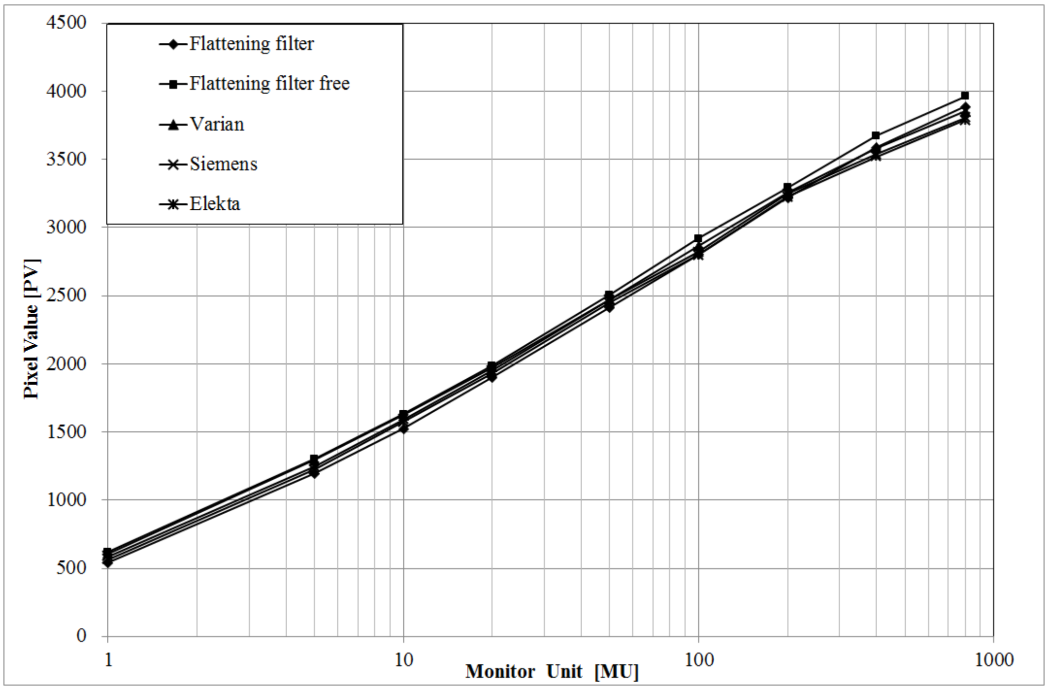

Figure 2 The R^2 value close to 1 shows stabilized linearity of the system. DR systems according to various period of use showed linearity that closed to 1 for the MTF measurements

Table 2 Value of the MTF and the DQE for the DR systems studied; MTF was evaluated for 50% and 10% points in the MTF curves at 1 mm^{-1} and the peak DQE and the DQE were calculated at 1 mm^{-1} by using 1 MU

Imaging systems	Spatial Frequency for MTF 50% (mm^{-1})	Spatial Frequency for MTF 10% (mm^{-1})	MTF at 1 mm^{-1}	Peak DQE	DQE at 1 mm^{-1}
Siemens BEAMVIEWPLUS	0.26	0.99	0.09	0.00026	2.32 E-05
Elekta iViewGT	0.26	0.93	0.08	0.0026	0.00014
Varian TrueBeamTM Flattening filter	0.37	1.07	0.16	0.0009	2.29 E-05
Varian TrueBeamTM Flattening filter free	0.46	1.40	0.22	0.0010	4.32 E-05
Varian Clinac® iX	0.23	0.78	0.05	0.00013	5.07 E-06

iViewGT, and Varian Clinac® iX aS1000 were 1.40, 1.07, 0.99, 0.93, and 0.78 mm^{-1}, respectively (Figure 3). The MTF (1 mm^{-1}), for Varian TrueBeam™ FFF, Varian TrueBeam™ flattening filter, Siemens BEAMVIEW^{PLUS}, Elekta iViewGT, and Varian Clinac® iX aS1000 were 0.22, 0.16, 0.09, 0.08 and 0.05, respectively (Figure 3).

3. Noise Power Spectrum (NPS)

Figure 4 shows the NPS profiles and shows the effect of additional Gaussian noise for the DR detectors in each direction. NPS spectra of the DR group were limited to spatial frequency of 1.2 mm^{-1} because of the small ROI and the big pixel size. DR detectors show a decreasing noise distribution with increase of the spatial frequency. Our study results, which indicate a decrease of noise distribution along with increase of spatial frequency, are similar to previous studies on in–direct detectors[1]. A low noise value means a better NPS results. The DR detectors we used are Varian TrueBeam™, Siemens BEAMVIEW^{PLUS}, Elekta iViewGT and Varian Clinac® iX aS1000. Elekta iViewGT showed the best noise distribution while the remaining detectors showed better noise distributions in the following order: Varian TrueBeam™ flattening filter, Varian TrueBeam™ FFF, Siemens BEAMVIEW^{PLUS} and Varian Clinac® iX aS1000 (Figure 4).

4. Detective Quantum Efficiency (DQE)

Table 2 lists the peak DQE and the DQE at a spatial frequency of 1 mm^{-1} for the four detectors; our data are indicated in Fig. 5. Our four DR detectors exhibited a high peak at a low spatial frequency, and they tended to decrease for spatial frequencies greater than 0.3 mm^{-1}.

The peak DQE for Varian TrueBeam™ flattening filter, Varian Truebeam™ FFF, Elekta iViewGT and Varian Clinac® iX aS1000 were 0.0009, 0.0010, 0.0026, 0.00026 and 5.07E–06, respectively (Fig. 5). The DQE of the Elekta iViewGT for a spatial frequency of 1mm^{-1} shows the highest value of 0.00014 , and while those for Varian TrueBeam™ FFF, Siemens BEAMVIEW^{PLUS}, Varian TrueBeam™ flattening filter and Varian Clinac® iX aS1000 were 4.32E–05, 2.32E–05, 2.29E–05 and 5.07E–06 (Figure 5).

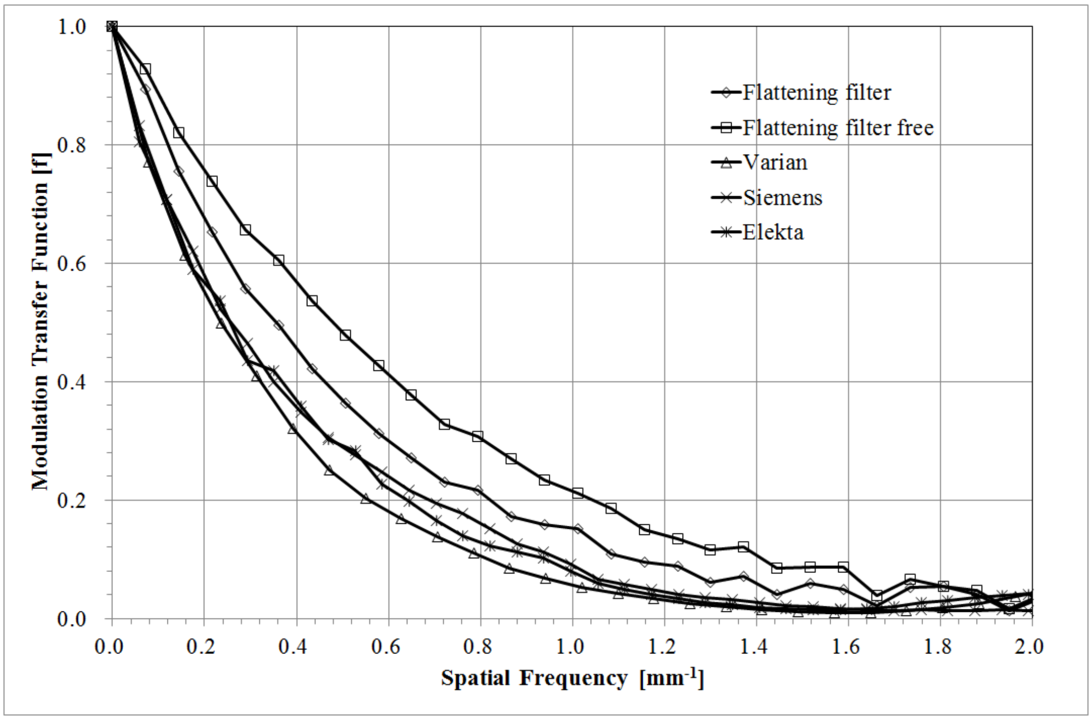

Figure 3 MTF curves for DR detectors using the edge method and MTF 50% and 10%; Varian TrueBeam™ flattening filter free indicated the best resolution efficiency

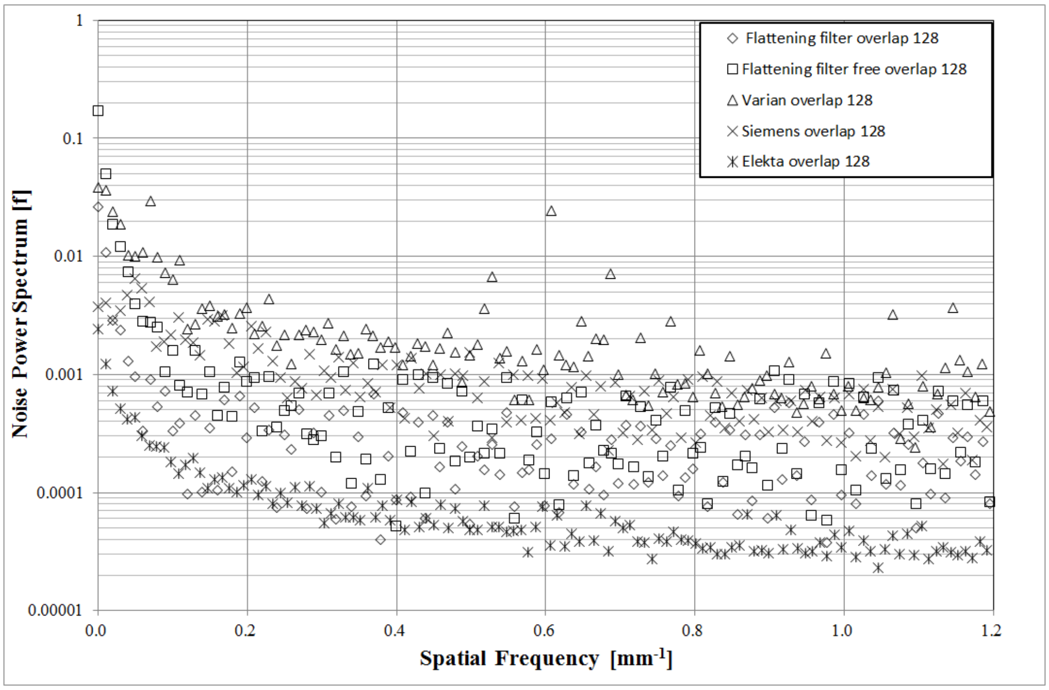

Figure 4 NPS spectrum of DR detectors by using overlapping. Elekta iViewGT indicated the best distribution, and Varian Clinac® iX aS1000 indicated the best noise distribution

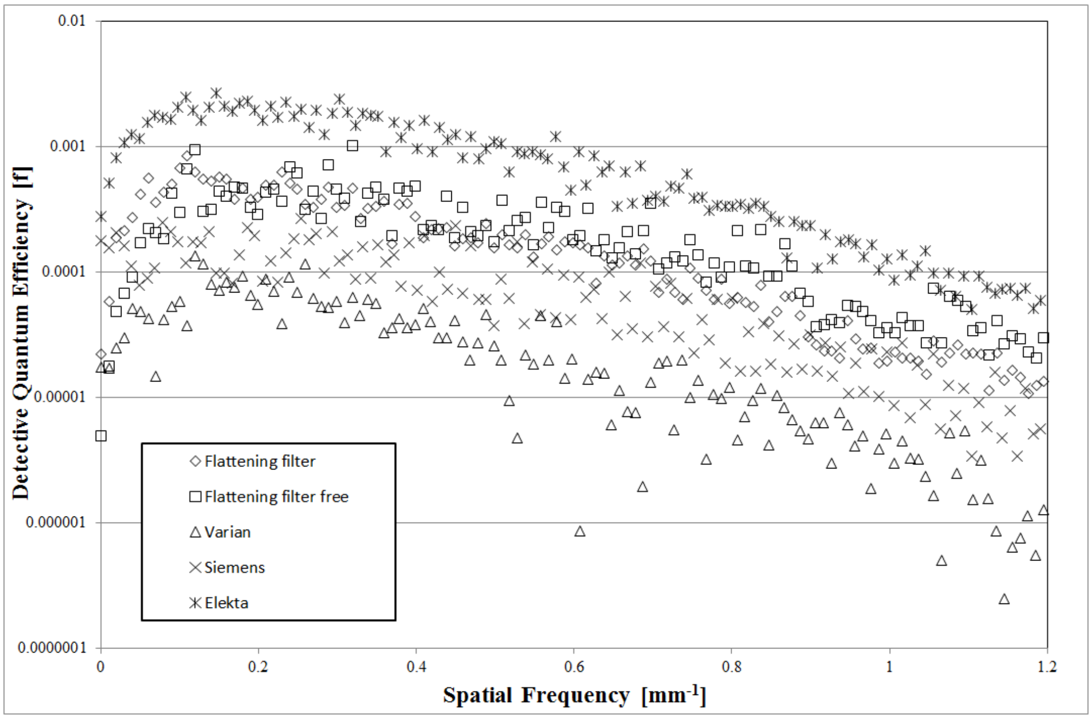

Figure 5 DQE was evaluated by using the measured MTF and NPS. Our DR detectors indicated high peaks at low spatial frequency whereas they indicated a decreasing aspect for frequencies greater than 0.3 mm^{-1}; Elekta iViewGT indicated the best efficiency for the DR detectors and Varian Clinac® iX aS1000 indicated the lowest efficiency. The efficiency sharply decreased at high spatial frequencies

Ⅳ. DISCUSSION

Among the MTF results, some of the differences were caused by detector's characteristics, which resulted from the differences regarding the materials and the conditions used in measuring the MTF. However, these differences did not affect the comparison of the methods because the MTF results similarly affect all the methods. Unlike diagnostic imagers, reported MTF measurements for megavoltage imagers have typically included the loss of resolution due to the focal spot that effectively characterize the Linac head related to the imaging system. In diagnostic imaging, the MTF contribution from the focal spot can be easily quantified based on spot size and magnification by assuming a step function source profile. However, megavoltage imaging requires measurements of the X-ray source profile that includes an asymmetric 2D primary source distribution as well as scatter off the flattening filter and primary collimators specific to each Linac. In the results, although Varian Clinac® iX aS1000 and Varian TrueBeam™ were made by the same manufacturer, Varian TrueBeam™ had a higher resolution and efficiency than Varian Clinac® iX aS1000. Varian Clinac® iX aS1000 had an older date of manufacture compared to Varian TrueBeam™. Therefore, Varian TrueBeam™ showed higher resolution and efficiency. Because two EPID systems had the same phosphor screen, differences of MTF are caused by reading array of a-Si and characteristic of changed Linac.

In the results, Varian TrueBeam™ flattening filter and Varian TrueBeam™ FFF showed a similar noise distribution. However, Varian TrueBeam™ FFF had the higher amplitude of noise, compared to Varian TrueBeam™ flattening filter. These results are caused by beam softening because of the absence of the flattening filter. Noise indicates uncertainty and it affects diagnosis and treatment. This uncertainty in the data can be reduced by using the overlapping factor, which overlaps ROIs.

NPS methodologies in radiation therapy, there is a difference between the NPS method of the 2D dose distribution and the penumbra and the flatness of the 3D dose distribution. Thus, we suggest that the penumbra and the flatness can be measured in a similar way to the NPS process. Thus, the penumbra and the flatness have noise property characteristics similar to there of the NPS. The NPS is made of contributions from initial quantum noise, Poisson surplus noise, second quantum noise and additional electronic noise. Therefore, the two-dimensional NPS provides the noise response in every direction. The NPS is related to the pixel arrangement. The additional mechanical noise is generally "white" (i.e., it has unity as a spatial frequency function) and does not include MTF information of the detector. Additional mechanical noise is structural as the exposure function whereas quantum noise is normalized to the exposure at the detector's exit. However, noise hardly affects the measurements because noise is included in all detectors[23)]. Therefore, the penumbra and the flatness were measured using the IEC 62220-1 RQA5 methodologies of the NPS and the normalized noise power spectrum (NNPS) was measured with the 2D FFT methods by using the white images. Thus, NPS is a very important element to describe the penumbra in the field of methodological MVI and noise properties of flatness in medical image systems. Thus, this study demonstrated the measurement of the NPS in the MVI field. Image processing is important to acquire an optimum radiation image. The NPS can be calculated by using identical methods that evaluate the quality.

The DQE of the digital MVI EPID was approximately 0.7 ~ 0.8 mm^{-1}[24)]. For the MTF data, a greater variation can occur for the DQE because of the dosimeter calibration differences, the MTF^2 dependence and the influence of NNPS conditioning. However, our results were approximately 1.0 mm^{-1} according to the increase in the spatial frequency, which is comparable to the values reported in the literature. The data indicated that the systems assessed in the current study by a common methodology achieved similar performances with respect to the DQE when compared against values common a MVI EPID.

Ⅴ. CONCLUSION

This study evaluated the MTF, NPS and DQE using edge block in MVI to maintain a high accuracy in delivering dose. In order to maintain such a high accuracy, we evaluated the performance of four DR systems which were used in clinic. Our results were approximately 1.0 mm^{-1} according to the increase in the spatial frequency, which is comparable to the values reported in the literature. In addition, MTF measurements allowed for fast computations of the DQE, a fundamental metric for detector image quality, and they allowed for inclusion of the DQE into routine clinical QA. The performance evaluation, such as MTF, NPS, and DQE, is important not only clinically but also as for the detector improvement. Therefore, this study could be incorporated into used in clinical QA requiring performance and EPID development research.

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•국문초록

방사선치료의 다양한 EPID 영상 질평가

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MV방사선 치료는 둘러싸여 있는 정상조직의 피폭선량을 최소화 하면서, target volume 내에 정확하게 선량을 전달하는데 있어 중요한 요인이다. 본 연구에서는 방사선 치료의 높은 정확성을 유지하기 위하여 megavoltage X-ray imaging (MVI)에서 edge block 을 사용한 digital radiography (DR) system 검출기의 modulation transfer function (MTF: 변조전달함수), the noise power spectrum (NPS: 잡음전력스펙트럼) and the detective quantum efficiency (DQE: 양자검출효율)를 측정하고자 한다.

우리는 텅스텐으로 구성된 19 (thickness) × 10 (length) × 1 (width) cm^3 의 edge block을 사용하였으며, 다음과 같은 setting들로 pre-sampling modulation transfer function (MTF)를 계산하였다: 6-megavolt (MV) energy를 사용하고, 다양한 Radiotherapy장비인 TrueBeamTM (Varian), BEAMVIEWPLUS (Siemens), iViewGT (Elekta), ClinacR iX (Varian) 를 사용하였다. MTF결과에서 Varian TrueBeamTM flattening filter free가 MTF의 50% (mm^{-1})에서 0.46, 10% (mm^{-1}) 에서 1.40로 가장 highest value를 보였다. Noise 분포는 Elekta iViewGT가 가장 낮은 분포를 보였다. DQE에서는 Elekta iViewGT가 peak DQE에서 0.0026 그리고 1 mm^{-1} DQE 에서 0.00014로 가장 높았다. 본 연구는 Edge method를 이용하여 MTF와 DQE산출을 재현하였으며, 현재 임상에서 사용되는 DR 시스템 측정의 높은 정확성을 유지할 수 있었으며 이러한 연구는 전통적인 QA 영상화뿐만 아니라 검출기 개발 연구에 있어서 정량적인 MTF, NPS, DQE 측정에 더욱 더 효율적으로 사용될 수 있다는 것을 알 수 있다.

중심 단어: 변조전달함수, 잡음전력스펙트럼, 양자검출효율, 전자포털영상장치