A Study of Optimized MRI Parameters for Polymer Gel Dosimetry

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In order to verify exact dose distributions in the state-of-the-art radiation techniques, a newly designed three-dimensional dosimeter and technique has been took strongly into consideration. The main purpose of our study is to verify the optimized parameters of polymer gel as a real volumetric dosimeter in terms of the various study of MRI. We prepared a gel dosimeter by combing 8% of gelatin, 8% of MAA, and 10 mM of THPC. We used a Co-60 gamma-ray teletherapy unit and delivered doses of 0, 2, 4, 6, 8, 10, 12, and 14 Gy to each polymer gel with a solid phantom. We used a fast spin-echo pulse to acquire the characterized T2 time of MRI. The signal noise ratio (SNR) of the head & neck coil was a relatively lower sensitivity than the body coil; therefore the dose uncertainty of head & neck coil would be lower than body coil's. But the dose uncertainty and resolution of the head & neck coil were superior to the body coil in this study. The TR time between 1,500 ms and 2,000 ms showed no significant difference in the dose resolution, but TR of 1,500 ms showed less dose uncertainty. For the slice thickness of 2.5 mm, less dose uncertainty of TE times was at 4 Gy, as well, it was the lowest result over 4 Gy at TE of 12 ms. The dose uncertainty was not critical up to 6 Gy, but the best dose resolution was obtained at 20 ms up to 8 Gy. The dose resolution shows the lowest value was over 20 ms and was an excellent result in the number of excitation (NEX) of three. The NEX of two was the highest dose resolution. We concluded that the better result of slice thickness versus NEX was related to the NEX increment and thin slice thickness.

Key Words: Polymer gel dosimeter, Optimized parameters, Dose resolution, MRI

INTRODUCTION

Due to the steep dose gradient and accurate dose distributions of recent radiation treatments or radiation surgical techniques in a small field treatment, an unnoticeable small dosimetric dose evaluation error may lead to serious side-effects or death for patients during treatments. Both the qualified radiation experts and well- organized professional institutions deal with this issue that should nowadays be significantly considered[1-3] One or two-dimensional dosimeter, ionization chamber, diode, thermoluminescent dosimeter (TLD), and film are heavily used for the evaluation of radiation dose delivery. Despite the fact that these dosimeters have been used for conventional radiation therapy dosimetry, its implementation to the modern complex radiation treatments, such as intensity modulated radiation therapy (IMRT), image guided radiation therapy (IGRT), stereotactic radiosurgery (SRS), and volumetric modulated arc therapy (VMAT) was somewhat limited due to the difficulty of measuring the exact dose distribution. Thus, a newly designed robust three-dimensional dosimeter and technique was strongly considered. Three-dimensional semiconductor

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detector arrays were recently reported to measure three-dimensional dose distribution directly, but these were not considered a real volumetric dosimeter due to the incomplete analysis of three-dimensional dose distribution.[4)]

A gel dosimeter was a considerable volumetric dosimeter used to measure the absorbed dose by means of the analyzing the chemical variance of radiation in the gel matrix. Several remarkable aspects of a polymer gel dosimeter were not only easy to handle, but also able to increase treatment position accuracy as well as obtaining the desired absorbed dose and dose distribution simultaneously by manufacturing a volumetric phantom. Meanwhile, acquisition of high spatial resolution was another positive aspect of a gel dosimeter due to the use of specific chemical variance. Since polymerization of acrylic monomer in the polymer gel dosimeter was dependent on the absorbed radiation dose in the gel matrix, it could be used for a various types of imaging devices which were required the variable density like other radiation chromic gel dosimeters.[5-9)] Imaging devices based on utilization of polymer gel dosimeter include: magnetic resonance imaging (MRI), X-ray computed tomography, optical computed tomography, ultrasound, and CCD camera image. MRI studies for gel dosimetry was very active due to the implementation of high dosimetric resolution. The dose calculation of polymer gel in the study of MRI used the variance of transverse relaxation time (T2) that was dependent upon the absorbed radiation dose.[10-23)] The adequate choice of parameters to acquire an accurate T2 time of MRI was pivotal in this gel dosimetry because it might influence the accuracy of dosimeters. For the T2 time of an MRI, the optimized parameter of image acquisition with the unique T2 time of materials was seriously considered. Implications of unique pulse sequences, echo spacing, echo numbers, repetition times, and the various type of coils with each polymer dosimeter was decided upon for this polymer gel dosimeter. Because the echo spacing significantly affected the accuracy of the T2 time and signal nose ratio (SNR) of a MRI, several studies were performed to find this condition. Deene et al. demonstrated the optimized echo time by using a Monte Carlo simulation.[15,26)]

In the former studies, we also analyzed the basic characteristics of a MRI with fabricating gel in our laboratory and confirmed an outstanding result as a one-dimensional dosimeter. To use a three-dimensional dosimeter, they further confirmed research about selection of the adequate time echo (TE) time, repetition time (TR) phase, image acquisition time, and image distortion correction such as a polymer gel that has been used as other monomers.[27)] The primary goal of our study is to verify the optimized parameters of polymer gel dosimeter for MRI studies. To do so, we applied several new concepts, dose uncertainties and dose resolutions, to evaluate the acquired images with each condition to help find the optimized parameters.

MATERIALS AND METHODS

1. Gel dosimeter and dose delivery

We prepared a gel dosimeter by fabricating 8% of gelatin (300 bloom, Sigma-Aldrich, USA), 8% of MAA (Metaacrylic acid, Sigma-Aldrich, USA), and 10 mM of THPC (Tetrakis hydroxymethyl phosphonium, Sigma-Aldrich, USA). Normoxic polymer gel 0.05 mM of HQ (Hydroquinone, Sigma-Aldrich, USA) also reported. Each fabricated gel sample in the lab was separated with several glass vials, which was 2 cm of diameter and 4 cm of height, and then wrapped those up with aluminum foil to avoid the room light. Those were kept in the refrigerator at 4°C. We used a Co-60 gamma-ray teletherapy unit (Theratron-780; AECL, Ottawa, Canada) and delivered the doses of 0, 2, 4, 6, 8, 10, 12, and 14 Gy to each polymer gel with a solid phantom.

2. Magnetic resonance image and transverse relaxation time

We minimized the temperature dependency of the gel samples kept them in the MRI room over 24 hours to be equivalent with the state of the room before the MRI scan. A 1.5 T MRI device (Magnetom Avanto, Toshiba Co, Japan) was used as a main scanner for dose evaluations. To measure the T2 time of polymer gel dosimeter in MRI, we used a specific head & neck coil which had characterized the circularly polarized (CP) and multiple spin-echo waveforms because they were able to acquire uniform T2 images within 120 mm from the center of core.[15)] To reduce the non-homogeneity effect of the magnetic field in terms of the position of each sample, we used a cylindrical stand with 15 cm diameter when scanning. For MRI scanning, three samples of polymer gel were deliv-

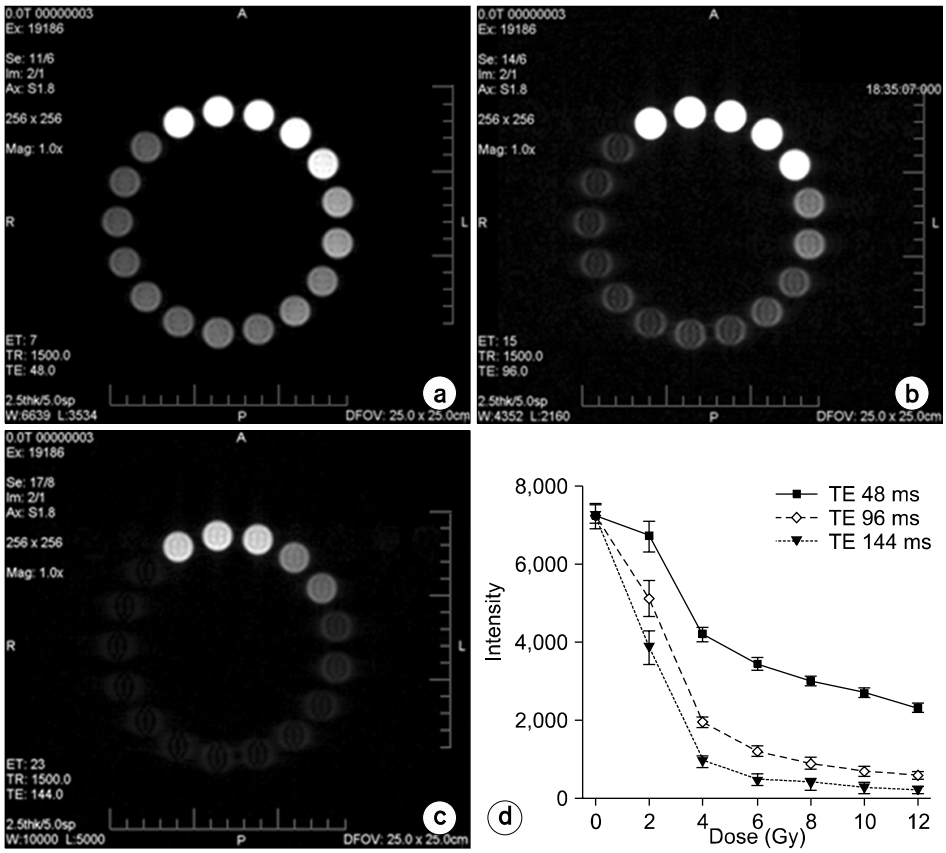

Fig. 1. The variance of pixel value in MRI image. Acquisition TE times (a) 48 ms, (b) 96 ms, (c) 144 ms, (d) The dose vs. pixel intensity curve.

ered 0 Gy and each of two samples was also delivered the doses of 2, 4, 6, 8, 10, 12, and 14 Gy. A total of 17 samples were put into a cylindrical phantom and then fixed (Fig. 1). We used a fast spin-echo waveform to acquire the characterized T2 time of MRI. In order to verify imaging characteristics and dosimetric dependency with acquiring a radio frequency (RF), we used a body coil and head coil and then compared each condition. We also divided each scanning time of 1,500 ms and 2,000 ms to verify the different imaging effects with repetition times (TR). Since echo time (TE) had a serious affect on T2 time, TE time was performed at 12, 15, and 20 ms. According to Deene's study,[15] the critical non-homogeneity effect of T2 images was found when TE time intervals differed from others in the multiple spin-echo method. Thus, our study chose 150 ms for TE time, due to the echo images, which showed the uncertainty of image calculation when applied 30 ms and 150 ms, respectively.

The TE time was from 36 ms to 144 ms for a TE space of 12 ms; from 35 ms to 145 ms for TE space of 15 ms; and from 40 ms to 140 ms for TE space of 20 ms. In order to verify thickness dependency, we acquired an MRI with the slice thickness of 2.5, 3.5, and 4.5 mm in each echo time. TE time was from 40 ms to 140 ms for TE space of 20 ms, and the slice thickness was 3, 4, and 5 mm for each echo time. The number of excitation (NEX) was 1, 2, and 3 to verify dependence of NEX. The dose analysis matrix of this study was 256×256 mm^2 and FOV (Field of View) was 250×250 mm^2. Since this study was based on the evaluation of gel dosimeter's dosimetric characteristics, we acquired only scanned images from several glass samples due to minimizing dosimetric error resulted from gel's temperature dependency and image distortion with multiple segmentation. The high frequency implication in study MRI's might lead to not only an increase in temperature of the gel phantom, but also affect on the T2 time.[15,26,28]

Acquired MRI Images were transferred to a DDCheck program, which was programmed by our lab. We used the C^{++} program for T2 calculation (Fig. 2). The calculation algorithm of T2 at the DDcheck program used a linear regression be-

tween the logarithm of the pixel intensities and the corresponding echo times. Each of the acquired images was reconstructed by R2 map. We then acquired R2 time and standard deviation with a pixel of 50 for a unique region of interest (ROI) of dose. The calculation of dose versus T2 fit curve was used a cubic function from sigma plot (Systat Software Inc, San Jose, California, USA).

3. Dose uncertainty and dose resolution

We implied new concepts, like dose uncertainty and dose resolution for dosimetric evaluation by the variable conditions of MRI.[25] Dose uncertainty in gel dosimeter was defined by the inaccuracy of dose determination in the characteristic curve of dose. The primary reason for dose uncertainty in gel dosimeter was known as various noises in the map of T2.

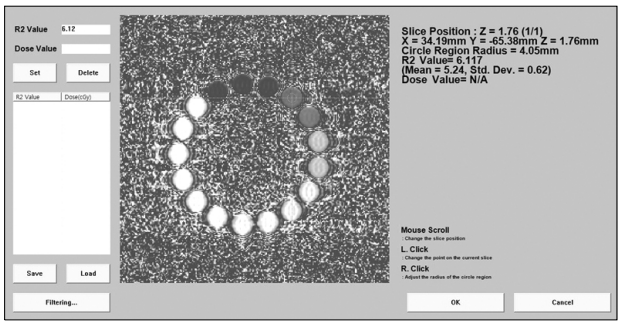

Fig. 2. The screen view of the DD-Check program, which was featured by the C^{++} program for T2 calculation.

We defined the combined standard uncertainty of dose without considering the randomized uncertainty as

$$u_c^2(D) = \left(\frac{\partial D}{\partial T2}\right)^2 u^2(T2) \quad (1)$$

Here, *u(T2)* was the standard uncertainty of the specific T2 time. So, the dose uncertainty resulted from dose versus T2's calibration curve should be considered the noise of T2 when using a differential equation curve.

$$u_c(D) = u(T2) \quad (2)$$

We calculated T2 and standard deviation *s(T2)* for each pixel, which referred to the specific ROI in the map of T2. The result of the experimental standard deviation was equivalent with the T2's standard deviation due to using a lot of pixels. We used two gel samples of polymer gel for the dose measurement.

Thus, when we used a and b as a sample of polymer gel, the extended standard deviation was

$$u(T2) = \sqrt{\frac{S^2(a,b)}{2} + S_a^2(T2) + S_b^2(T2)} \quad (3)$$

Here, *S* (a, b) was the standard deviation of T2 between the two samples, as well $S_a(T2)$ and $S_b(T2)$ were the relative

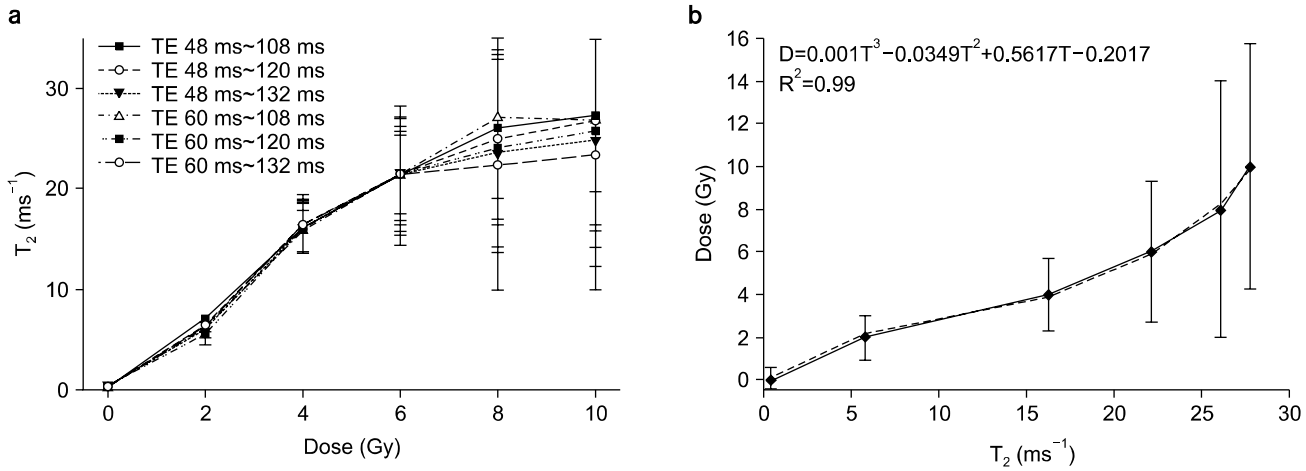

Fig. 3. The magnificent difference of MRI resulted from the dose with T2 time calculation. (a, b) T2-Dose. The optimized condition for fit considering the radiation dose was from 40 ms to 110 ms of TE. It shows the T2's curve and curve fitted formula when applied from 48 ms to 108 ms of TE.

standard deviation of T2. The relative standard deviation was defined as *u(T2)/T2*. Dose resolution affected to the dose uncertainty and dose sensitivity due to the variance of T2. So, the standard deviation of each dose was defined as σ_D. In addition, we defined the dose resolution within 95% as

$$D_{\Delta}^{95\%} = 2.77\sigma_D \quad (4)$$

RESULTS

1. Calculation of transverse relaxation time

To verify the optimized transverse relaxation time parameters, we calculated T2 time curve with changing of period of echo space (ES) and number of TE images dealt with calculation of T2 time. We compared with the dose linearity and standard deviation in terms of the T2 curve. Fig. 3(a) shows the curve of T2 time with the images of TE when we applied ES of 12 ms. For the ES of 12 ms, when implied TE time to T2 time before the ES of 48 ms, we confirmed that the dose linearity was drastically decreased from 0 Gy to 2 Gy, as well the result of standard deviation was also were rapidly fluctuated. From the TE of 48 ms, we could acquire images of 108 ms, 120 ms, and 132 ms and T2's curve. Meanwhile, we compared to the last acquired images of 108 ms, 120 ms, and 132 ms with the TE of 60 ms. We confirmed the magnificent

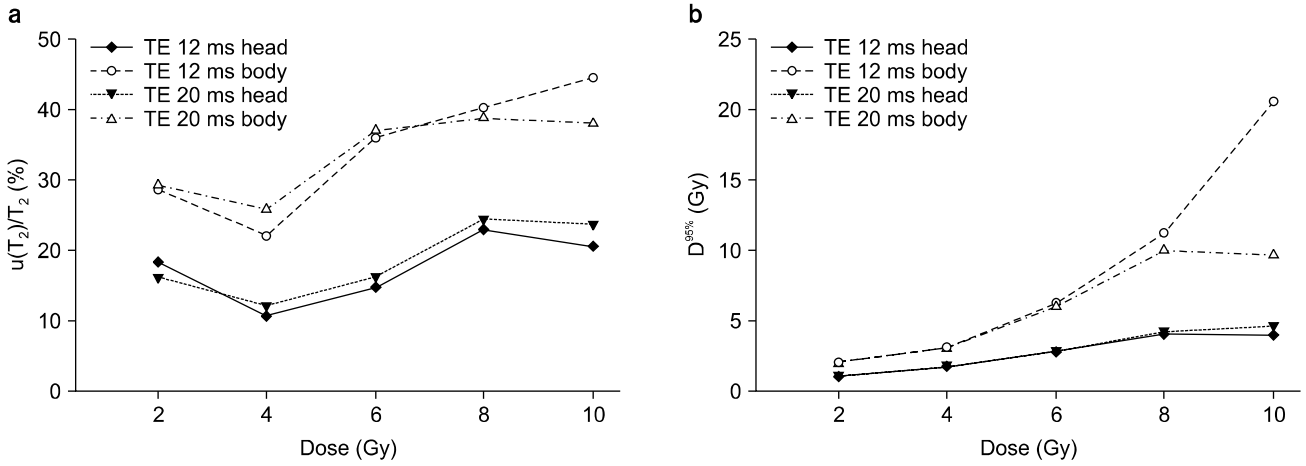

Fig. 4. A variation of dose uncertainty with coil type: (a) Dose uncertainty, (b) Dose resolution. TR time study between 1,500 ms and 2,000 ms, it showed no significant variance of dose resolution, but for TR of 1,500 ms, less dose uncertainty was shown.

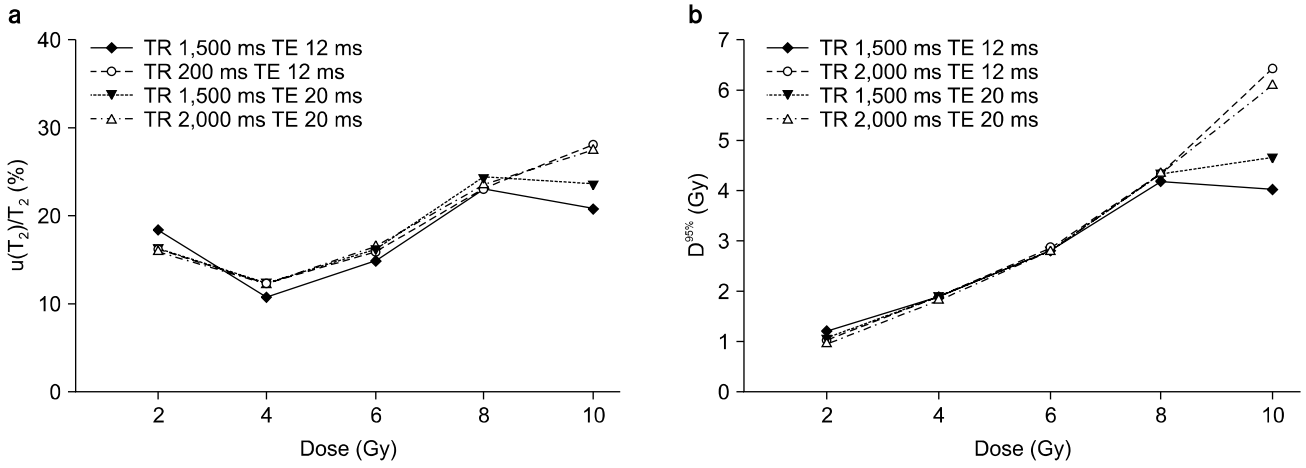

Fig. 5. The study of various TR times: (a) Dose uncertainty, (b) Dose resolution.

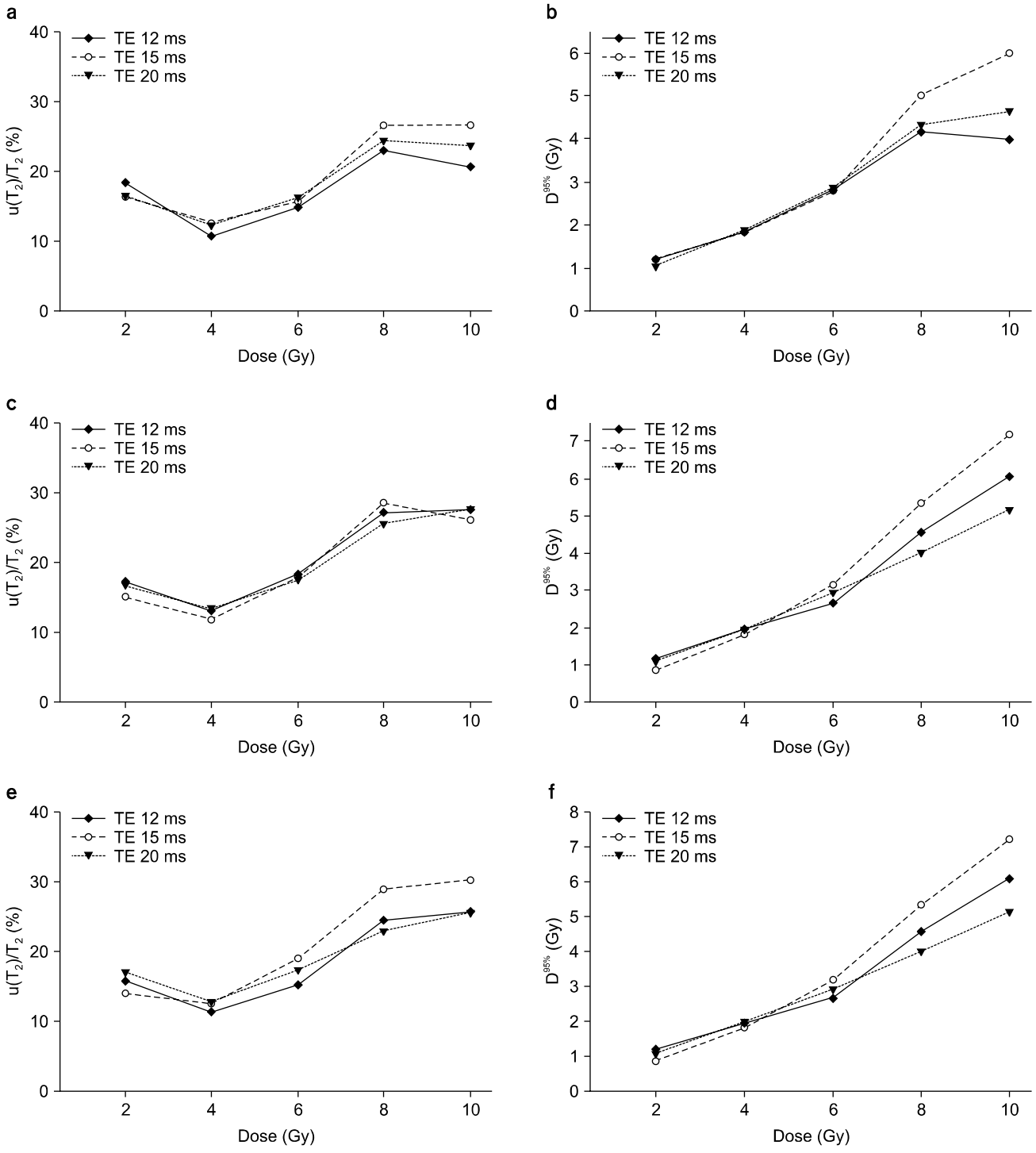

Fig. 6. The curve of the dose uncertainty and dose resolution concerning the segment thickness and TE time with MRI: (a) 2.5 mm Dose uncertainty, (b) 2.5 mm Dose resolution, (c) 3.5 mm Dose uncertainty, (d) 3.5 mm Dose resolution, (e) 4.5 mm Dose uncertainty, (f) 4.5 mm Dose resolution.

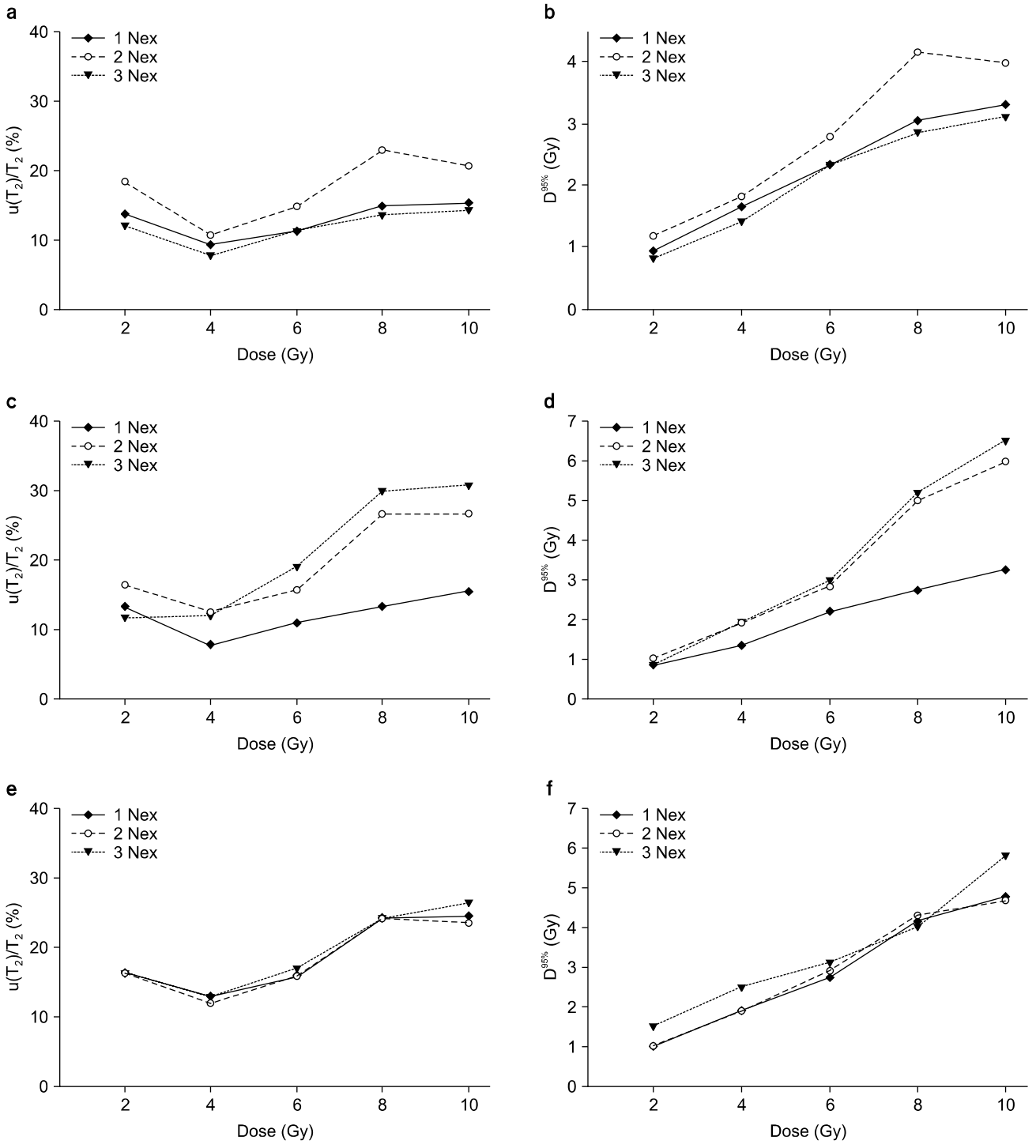

Fig. 7. The curve of dose uncertainty and dose resolution regarding the thickness of segmentation and NEX: (a) 2.5 mm Dose uncertainty, (b) 2.5 mm Dose resolution, (c) 3.5 mm Dose uncertainty, (d) 3.5 mm Dose resolution, (e) 4.5 mm Dose uncertainty, (f) 4.5 mm Dose resolution.

difference of MRI resulted from the dose in the Fig. 3(a). The optimized condition for fitting concerning the radiation dose was from 40 ms to 110 ms of TE. Fig. 3(b) shows the T2's curve and curve fitted formula when applied from 48 ms to 108 ms of TE. R^2 was an outstanding result of 0.99, and we could convert T2 time to dose with these formula.

2. Coil study and TR study

Generally, as signal noise ratio (SNR) of head & neck coil was a relatively lower sensitivity than body coil, the dose uncertainty of head & neck coil would be lower than body coil's. On the other hand, the image uniformity of the body coil brought a better result than head & neck coil from the result of other studies.[15] We performed the evaluation of dose uncertainty and resolution in terms of the head and body coil using the TE's period of 12 ms and 20 ms. The results demonstrated that the dose uncertainty and resolution of head & neck coil were superior to body coil in the Fig. 4. The result of the dose resolution of head & neck coil, particularly, was stable within 5% up to 10 Gy, but that of body coil was within 10% up to 8 Gy. For TR time study between 1,500 ms and 2,000 ms, it showed no significant variance of dose resolution. We decided TR time of 1,500 ms due to less dose uncertainty in the Fig. 5.

3. TE study

Fig. 6 shows the curve of the dose uncertainty and dose resolution concerning about the segment thickness and TE time with MRI. For the slice thickness of 2.5 mm, we confirmed the less dose uncertainty of TE time at 4 Gy. We also found the lowest result over 4 Gy in case of the TE of 12 ms in Fig. 6(a). A dose uncertainty up to 6 Gy was not variable with the TE time, but a better result was 12 ms of TE in Fig. 6(b). For the slice thickness of 3.5 mm, we confirmed that the remarkable less dose uncertainty was at 4 Gy. The lowest dose uncertainty in the entire dose was at 15 ms of TE, but it was not critical in Fig. 6(c). The dose uncertainty was not critical up to 6 Gy, but the best dose resolution was at 20 ms up to 8 Gy in Fig. 6(d). For the slice thickness of 4.5 mm, we found that the dose uncertainty of 2 Gy was at 15 ms of TE. From 4 Gy to 6 Gy, it was at 12 ms, as well as the worse value of 20 ms in Fig. 6(e). The dose resolution shows the lowest value over 20 ms, even though the result of it is not variable up to 6 Gy in the Fig. 6(f).

Fig. 7 shows the curve of dose uncertainty and dose resolution regarding the thickness of segmentation and the NEX. For the slice thickness of 2.5 mm, the NEX of three was the lowest dose uncertainty in Fig. 7(a). Meanwhile, the dose resolution also was an excellent result for the NEX of three, and we confirmed that a NEX of two was the highest dose resolution in Fig. 7(b). For the slice thickness of 3.5 mm, the NEX of 1 was outstanding for the dose uncertainty and resolution in Fig. 7(c). For the slice thickness of 4.5 mm, the dose uncertainty was not significant with variance of NEX in Fig. 7(e), but the dose resolution in the NEX of one and two showed a slightly less value up to 6 Gy in Fig. 7(f).

DISCUSSION AND CONCLUSION

To get an accurate T2 time, it needed a large amount of time for TR and a number repetitions for TE in the spin echo sequence.[29] However, the result of this study showed that T2 time was not dependent on the TR time rather than the less TE. We analyzed the imaging variance with various types of coils without using the dose distribution and confirmed that head & neck coil brought an outstanding result of image variance due to the effects of SNR. The Polymer gel that delivered a high dose was manufactured over a short time for T2 due to the manufacturing of high density of material that was a result of radiation exposure. In MRI studies, in order to get the optimized contrast images which depend upon the time of T2, we selected the average time of T2 as the time of TE. To determine an appropriate clinical approach, we considered the reasonable dose and selected the appropriate TE time due to the variance of the delivered dose for each sample. Unlike the result of former studies,[25,26] we found variables of TE with the slice thickness, as well we confirmed that a short TE was a better outcome of the dose uncertainty and dose resolution when it comes to having a thin segmentation and low dose. In contrast the dose uncertainty in the case of the thick segmentation was outstanding in a short TE, but a relatively long TE brought a better result in the high dose area. As the signal to noise ratio (SNR) of MRI was dependent on the dose reconstruction and dose accuracy, we needed to not only per-

form several MRI scans for the average image, but also extend the acquiring time of the signal to improve the quality of images.[15] We concluded that the better result of slice thickness versus NEX was related to the NEX increment and thin slice thickness. Based on the results of our study, further research should be considered concerning other predictable parameters when it comes to changing MRI scanners.

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중합체 겔 선량측정법을 위한 최적의 자기공명영상 변수에 관한 연구

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최신 방사선 치료 및 수술 기법에는 복잡한 3차원적 선량분포를 정확히 측정하는 실용적 선량분석 기기 및 기술이 필요하다. 본 연구에서는 실험실에서 제작한 겔을 방사선 치료 영역에서 선량계로 활용하기 위해 최적화된 자기공명영상 변수 조건에 대해 연구하였다. 이를 위해 각 자기공명영상 획득 조건에서 TE 시간 TR 시간, 영상 두께, 코일 등을 달리하여 조건 별로 획득한 영상을 이용하여 비교 평가하였고, 선량불확도 및 선량 분해능을 도입하여 본 연구에서 찾은 조건에 대해 평가하였다. 8% 젤라틴(300 bloom, Sigma-Aldrich, USA), 8% MAA (Metaacrylic acid, Sigma-Aldrich, USA), 10 mM THPC (tetrakis hydroxymethyl phosphonium, Sigma-Aldrich, USA), 그리고 0.05 mM HQ (Hydroquinone, Sigma-Aldrich, USA) 농도의 조성비를 가진 정상산소 중합체 겔을 실험실에서 합성하였다. 방사선 선량 전달은 Co-60 감마선 조사기 (Theratron-780; AECL, Ottawa, Canada)를 사용하였고 고체 팬텀을 사용하여 중합체 겔에 각각 0, 2, 4, 6, 8, 10, 12, 14 Gy의 선량을 전달하였다. 자기공명영상 장치의 특성상 T2 시간을 얻기 위해서는 fast spin echo 파형을 사용하였다. 일반적으로 Head Coil이 SNR이 Body coil 보다 낮아 선량 불확도가 우수할 것으로 예측하였으나, 일부 문헌에서는 Body coil이 영상 균일도가 우수하다고 하였다. 하지만 본 연구에서는 Head coil이 선량 불확도 및 선량 분해능이 모든 선량 영역에서 Body coil 보다 우수한 것을 확인하였다. TR 시간 연구에서 TR 1,500 ms와 TR 2,000 ms 간의 차이는 선량분해능에서 모두 큰 차이가 없으나 TR 1,500 ms가 조금 낮은 선량 불확도 값을 갖는 것을 보았다. MR 영상 두께가 2.5 mm일 경우 모든 TE 시간에 대해 4 Gy에서 가장 낮은 선량 불확도 값을 가졌다. 특히 TE 12 ms 경우 4 Gy 이후에는 가장 낮은 값의 결과를 얻었다. 선량 불확도의 경우 6 Gy까지는 TE 시간에 따른 차이는 없으나 이후에는 TE 12 ms가 가장 나은 결과를 얻었다. 선량 불확도의 겨우 6 Gy까지는 모든 TE 시간에 대해 차이가 미미하나 8 Gy 이상에는 20 ms가 가장 우수한 선량 분해능 값을 가졌다. 선량 분해능 값 역시 NEX 3에서 가장 우수한 값을 가졌고 2 NEX일 때 가장 높은 분해능 값을 가졌다. 본 연구 결과 영상 두께와 NEX의 결과는 영상 두께가 얇은 경우 NEX가 높을수록 우수한 결과를 얻었고 영상 두께가 두꺼워 질수록 NEX가 낮아야 함을 확인했다.

중심단어: 중합체 겔 선량계, 최적화 변수, 선량 분해능, 자기공명영상