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Magnetic Field–Based Dose Modulation in Diagnostic Radiology: A Feasibility Study

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This study evaluated whether a static magnetic field can modulate the electron-associated component of dose during diagnostic electromagnetic photon beam exposures. Doses were measured with a solid-state dosimeter at 60–110 kVp (10-kVp steps) on an X-ray radiation generator operated at 200 mA, 100 cm source-to-detector distance, 1.0 s, and 20 × 20 cm field. For each kVp, 20 repeated measurements were acquired under two conditions: no field versus a transverse ~0.5 T field generated by Nd magnets; output reproducibility was verified (all CV ≤ 0.05). With the field applied, doses were consistently but slightly lower at 60–90 kVp (all two-sided P > 0.05). Statistically significant reductions appeared at higher kVp: 100 kVp, 21.325 ± 0.155 vs 21.245 ± 0.076 mGy (P = 0.048); 110 kVp, 24.970 ± 0.108 vs 24.910 ± 0.072 mGy (P = 0.047). These findings support the feasibility of magnetic-field–induced dose modulation under diagnostic-energy conditions.

Keywords : diagnostic radiation, X-ray, electron fluence, dose reduction

1. Introduction

Electromagnetic radiation is routinely used in medicine for both diagnosis and therapy [1-3]. A central concern associated with the generation and clinical use of such radiation is exposure to ionizing radiation. Patient protection is a recognized priority in medical exposures. Radiation therapy mainly uses high-energy photon and electron beams for cancer treatment, whereas diagnostic imaging employs comparatively low-energy electromagnetic photon beam to form transmission images. To avoid unnecessary exposure in diagnostic and interventional radiology, patient doses must be managed in accordance with the principles of justification and optimization [4].

Effective dose, expressed in sieverts (Sv), is commonly used as a risk-related quantity to represent stochastic detriment from ionizing radiation in humans. In South Korea, the annual per-capita effective dose from medical diagnostic procedures is approximately 1.4 mSv, of which general radiography contributes about 0.44 mSv (≈32%) [5].

According to the International Commission on Radiological Protection (ICRP), ionizing radiation relevant to radiological protection includes alpha particles, beta particles (electrons and positrons) particles, electromagnetic photons (X-rays and gamma rays), and neutrons; among these, X-rays are predominantly used in diagnostic radiology [6]. X-ray emission from a tube comprises bremsstrahlung with a continuous energy spectrum influenced by tube voltage and current, and characteristic X-rays with discrete energies determined by the anode material. During diagnostic X-ray generation, a substantial fluence of primary and secondary electrons is also produced; this fluence depends on the selected tube voltage and current [7]. These electrons contribute substantially to energy deposition in human tissue and therefore influence patient dose and radiological protection [8].

Because charged particles are deflected in magnetic fields, several experimental and computational studies have investigated magnetic deflection of electron fluence to modulate dose distributions [9-14]. In high-energy electromagnetic photon radiotherapy, electron trajectories have been altered using permanent magnets with 0.5 T [9, 10], and application of a transverse field of 0.3 T has been reported to deflect electron fluence and reduce doses

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to adjacent tissues in rectal-cancer treatment [15]. Neodymium-based (Nd–Fe–B) permanent magnets, owing to their high remanence, have been commonly adopted for this purpose [9, 10, 15, 16]. Consequently, magnetic deflection of electron fluence can materially influence patient exposure. However, most prior investigations have focused on high-energy therapeutic photon beams; studies under diagnostic X-ray conditions remain scarce. The therapeutic radiation beams operate in the 4–15 MV energy range, whereas diagnostic X-ray beams are generally used at tube potentials of approximately 40–150 kVp. Because of this difference in beam energy, the level of electron contamination also differs, and consequently most related studies have been restricted to therapeutic radiation.

This study was initiated as a foundational investigation to quantify the contribution of electrons generated during diagnostic X-ray procedures to patient dose and to explore mitigation using magnetic fields. Accordingly, we expanded prior diagnostic-radiation work by extending the X-ray tube-voltage (kVp) range and evaluated the feasibility of using a static magnetic field from Nd permanent magnet to modulate the electron-associated dose component in diagnostic X-ray beams [17].

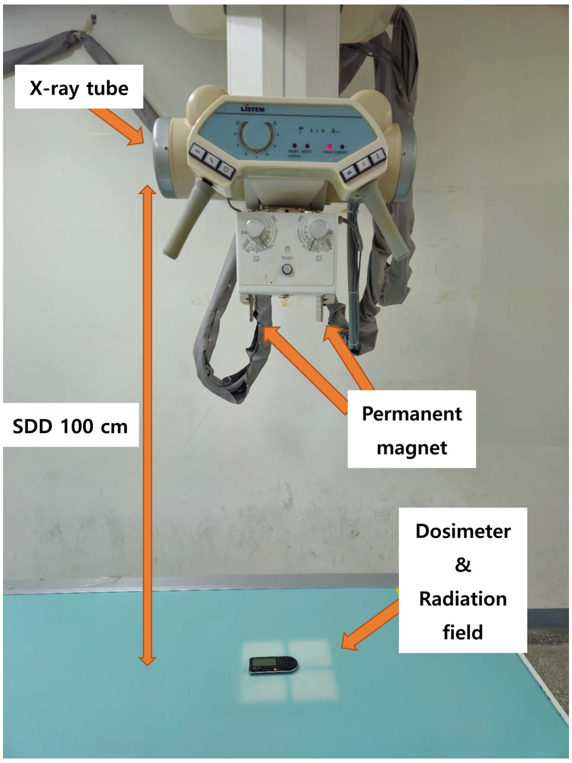

Fig. 1. (Color online) Photo of the setup showing the beam exposure direction and position of magnet/dosimeter (with radiation field size).

2. Materials and Methods

Radiation exposures were performed using a high-frequency radiation generator (REX-650R, Listem, Korea; 64 kW, 40–150 kVp, up to 640 mA at 100 kVp) equipped with a rotating-anode X-ray tube (LTN-50, 0.6/1.2 mm focal spots, 12° target angle, 150 kVp maximum, 300 kHU heat capacity). This generator was powered from a three-phase 380 V (±10 %) mains supply at 50/60 Hz.

At each tube-voltage (kVp) setting, twenty repeated measurements were acquired under two conditions—without a magnetic field and with a static field generated by Nd based permanent magnets—and the two data sets were compared.

As shown in Fig. 1, the radiation generator was operated under fixed conditions: tube current, 200 mA; source-to-detector distance (SDD), 100 cm; exposure time, 1.0 s; field size, 20 × 20 cm considering the detector plane area. All measurements were performed in air at room temperature (20–25 °C) and approximately atmospheric pressure (~101 kPa).

To assess variation in electron contribution as a function of tube potential (kVp), X-ray exposures were delivered in 10-kVp increments from 60 to 110 kVp, spanning common diagnostic settings. Radiation doses were measured with a solid-state multiparameter dosimeter (ThinX RAD, Unfors RaySafe, Sweden; automatically measuring tube potential [kVp], air kerma, dose rate, exposure time, pulse number, and half-value layer [HVL] in diagnostic radiation beam qualities). All radiation measurements in this study were recorded and reported in milligray (mGy), the SI unit of radiation absorbed dose.

To verify output reproducibility of the diagnostic X-ray generator used in this study, the coefficient of variation (CV) was calculated for each exposure setting. For CV assessment, at least five repeated exposures were acquired under identical conditions, and the CV was calculated from the resulting dose readings by the following formula:

$$CV = \frac{SD}{\bar{X}} = \frac{1}{\bar{X}}\left(\Sigma_{i=1}^{n}\frac{(X_i - \bar{X})^2}{n-1}\right)^{\frac{1}{2}} \quad (1)$$

In accordance with regulation on the safety management of diagnostic X-ray generator, the CV for a diagnostic X-ray generator shall be ≤ 0.05 [18]. In Eq. (1), CV denotes the coefficient of variation; SD, the sample standard deviation of the radiation dose measurements; $\bar{X}$, the mean of the radiation dose measurements; X_i, the i-th radiation dose measurement; and n, the number of measurements.

Two plate-shaped permanent magnets (10 × 5 cm each) were mounted on both sides immediately below the collimator aperture so that the exiting beam traversed the magnetic field; the gap between magnets was 15 cm. A static magnetic field was oriented along the tube's cathode–anode axis and transverse to the central X-ray beam axis. The surface magnetic flux density was ≈0.5 T, verified with a teslameter (TM-801EXP; Kanetec, Japan).

At each tube-voltage setting, radiation doses measured with the magnetic field were compared with those measured without the field under identical exposure settings. Data were analyzed with SPSS Statistics, version 26 (IBM, USA). Statistical significance was defined as two-sided $P < 0.05$. Homogeneity of variances was assessed; independent-samples t-tests (with the equal-variances assumption applied as appropriate) were then performed, and exact two-sided P values were reported.

3. Results

In this study, tube current, source-to-detector distance, exposure time, and field size were fixed, and radiation dose was measured with tube voltage (kVp) as the only independent variable, tested at six discrete settings (60, 70, 80, 90, 100, and 110 kVp). This design was used to evaluate how a magnetic field alters dose as a function of tube voltage.

Summary data are given in Table 1, and the dose–voltage trend is depicted in Fig. 2. Output reproducibility of the X-ray generator was verified by the coefficient of variation (CV = SD/mean) for repeated exposures at each setting; all CVs were < 0.05 (Table 2).

At 60–90 kVp, doses measured with the magnetic field were consistently, but slightly, lower than those without the field, and the differences were not statistically significant (independent-samples t test, two-sided $P >$ 0.05): 60 kVp, 9.035 ± 0.160 vs 8.980 ± 0.132 mGy (P = 0.243); 70 kVp, 11.105 ± 0.211 vs 11.015 ± 0.114 mGy (P = 0.104); 80 kVp, 15.385 ± 0.087 vs 15.340 ± 0.068 mGy (P = 0.077); and 90 kVp, 17.960 ± 0.139 vs 17.885 ± 0.099 mGy (P = 0.058). At higher tube voltages, the differences reached statistical significance: 100 kVp (21.325 ± 0.155 vs 21.245 ± 0.076 mGy; P = 0.048) and 110 kVp (24.970 ± 0.108 vs 24.910 ± 0.072 mGy; P = 0.047).

Table 1. The results of measured dose in two sample T-test by using magnetic field in each tube voltage.

Tube Voltage	Absorbed Dose		p
	Non Magnetic Field	Magnetic Field	
60	9.035 ± 0.160	8.980 ± 0.132	0.243
70	11.105 ± 0.211	11.015 ± 0.114	0.104
80	15.385 ± 0.087	15.340 ± 0.068	0.077
90	17.960 ± 0.139	17.885 ± 0.099	0.058
100	21.325 ± 0.155	21.245 ± 0.076	0.048
110	24.970 ± 0.108	24.910 ± 0.072	0.047

Tube voltage [kVp]
Absorbed dose : mean ± SD [mGy]
p : p-value

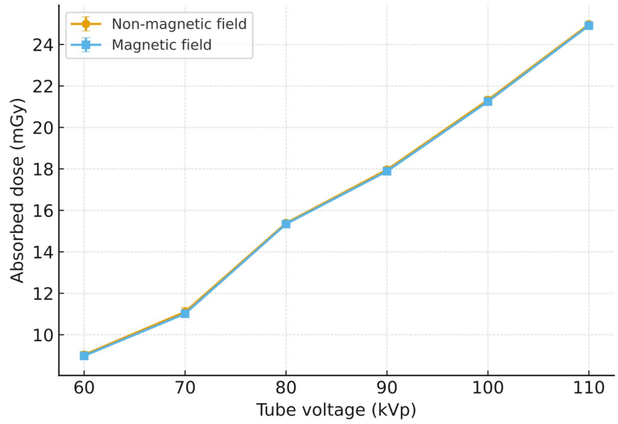

Fig. 2. (Color online) Results of measured radiation dose by tube voltage with and without applied magnetic field.

Table 2. Coefficient of variation at each tube voltage.

Tube Voltage	Coefficient of variation	
	Non Magnetic Field	Magnetic Field
60	0.0177	0.0147
70	0.0190	0.0103
80	0.0056	0.0044
90	0.0077	0.0055
100	0.0073	0.0036
110	0.0043	0.0029

Tube voltage [kVp]

4. Discussion

This study set out to quantify patient dose attributable to electrons generated concomitantly with bremsstrahlung in a diagnostic X-ray generator used for general radiography, and to explore, as a preliminary investigation, the feasibility of mitigating such dose.

Application of a 0.5 T static magnetic field under diagnostic energy X-ray conditions produced a small but measurable difference relative to the no-field condition. In prior preliminary measurements under identical exposure settings, no difference was detected with a 0.3 T field, whereas a modest difference emerged at 0.5 T in the present study. These observations suggest that stronger magnetic fields may yield more pronounced effects; however, confirmation across broader exposure conditions is required.

In the study of Ahn et al., use of a 0.5 T Nd permanent magnet during high-energy photon irradiation modulated the electron-associated component of dose, reducing dose to selected regions by approximately 30 % [9,10]. Je et al. reported that permanent magnets of 0.08 T, 0.37 T, and 0.5 T reduced the surface dose in electron-beam irradiation by up to 27 % [12]. Moreover, Jung et al. evaluated that applying a relatively low field of 0.3 T in 6 MV electromagnetic photon beam therapy decreased the radiation delivered dose to normal tissues by as much as 33.1 % [15].

Most related investigations have focused on therapeutic high-energy electromagnetic beams. This trend is likely because the higher energies and longer irradiation times in radiotherapy increase the relative contribution of electrons to dose delivery, enabling statistically significant modulation even at lower magnetic-field strengths.

Accordingly, prior research has largely been limited to radiotherapy, with few investigations focused on diagnostic-energy X-ray exposures. Consequently, diagnostic-energy X-ray conditions remain comparatively under-studied.

By applying magnetic-field–induced dose modulation to diagnostic X-ray examinations, the present work evaluates feasibility and, if further developed, could contribute a practically relevant factor to dose management in diagnostic radiology.

Within this study, a slight increase in the electron-associated dose change was observed as tube potential increased within the diagnostic X-ray range. Future work should extend to tube potentials approaching the upper bound used in general radiography, investigate stronger static fields (~1.0 T), and include longer irradiation times such as fluoroscopy.

Comprehensive parametric studies of exposure settings and magnet placement, complemented by Monte Carlo simulations, are warranted to map dose-modulation behavior across these variables. Considering the limitations of the detector employed in this study, subsequent dosimetry using ionization chambers and radiochromic film is recommended. The semiconductor detector used in this study exhibits high sensitivity for the measurement of low-energy X-rays. However, ionization chambers and film dosimeters are expected to be more suitable for characterizing the low-energy component of electron contamination because of their dosimetric properties. An ionization chamber is appropriate for assessing overall changes in dose, including the contribution from electron contamination. Film, owing to its very small thickness and dose detecting at the surface, is expected to provide detailed information on the contribution of electron dose. Nevertheless, it should be noted that the use of film has been decreasing because a separate processing procedure is required. Another important consideration is that when semiconductor detectors or ionization chambers are positioned in close proximity to the magnetic field, the electron flow in their readout circuitry may be influenced by the magnetic field. Therefore, it is necessary to maintain an adequate distance between the detector electronics and the magnetic field region during measurements.

In diagnostic X-ray systems, a few physical and geometrical parameters govern the extent to which electron contamination contributes inappropriately to the delivered dose. The added filtration of the X-ray tube can reduce the escape of primary electrons, but it is also associated with the production of secondary radiation and modifications of the beam quality. The tube current–time product (mAs) and the irradiation field size likewise tend to increase the effective electron contamination delivered to the irradiated object. In addition, the level of electron transport to the subject is expected to depend on the position of the magnetic field generated by the magnet relative to the source and the irradiated region. Future studies should therefore systematically vary these parameters and combine simulations with experimental measurements to more comprehensively characterize their influence.

5. Conclusions

The present study conducted a preliminary investigation under diagnostic-energy radiation conditions to examine changes in the electron-associated component of dose when a magnetic field was applied. Through experimental measurements, we observed feasibility—in terms of measurable alteration of the electron-associated dose component—of applying magnetic fields under diagnostic-energy conditions. In diagnostic radiation exposures performed at relatively high tube voltages (kVp), the small but statistically significant differences observed in applying the magnetic field can be attributed to the sufficiently high energies of the generated electrons.

This implies that, in examinations of thicker body regions, the use of higher tube voltages produces higher-energy electrons and, large patient thickness effectively brings the body surface closer to the radiation source, the influence of the electron dose component becomes more pronounced. Accordingly, the present findings are expected to provide meaningful baseline data for such clinical situations. Rarely addressed in the literature, this foundational study may inform dose reduction and image quality improvement in diagnostic-energy X-ray imaging.

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