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<원저>

A Study of Decrease Exposure Dose for the Radiotechnologist in PET/CT

-PET-CT 검사에서 방사선 종사자 피폭선량 저감에 대한 방안 연구-

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— Abstract —

Positron emission tomography scan has been growing diagnostic equipment in the development of medical imaging system. Compare to 99mTc emitting 140 keV, Positron emission radionuclide emits 511 keV gamma rays. Because of this high energy, it needs to reduce radioactive emitting from patients for radio technologist. We searched the external dose rates by changing distance from patients and measure the external dose rates when we used shielder investigate change external dose rates. In this study, the external dose distribution were analyzed in order to help managing radiation protection of radio technologists.

Ten patients were searched (mean age: 47.7 ± 6.6, mean height: 165.5 ± 3.8 cm, mean weight: 65.9 ± 1.4 kg). Radiation was measured on the location of head, chest, abdomen, knees and toes at the distance of 10, 50, 100, 150, and 200 cm, respectively. Then, all the procedure was given with a portable radiation shielding on the location of head, chest, and abdomen at the distance of 100, 150, and 200 cm and transmittance was calculated.

In 10 cm, head (105.40 μSv/h) was the highest and foot(15.85 μSv/h) was the lowest. In 200 cm, head, chest, and abdomen showed similar. On head, the measured dose rates were 9.56 μSv/h, 5.23 μSv/h, and 3.40 μSv/h in 100, 150, and 200 cm, respectively. When using shielder, it shows 2.24 μSv/h, 1.67 μSv/h, and 1.27 μSv/h in 100, 150, and 200 cm on head. On chest, the measured dose rates were 8.54 μSv/h, 4.90 μSv/h, 3.44 μSv/h in 100, 150, and 200 cm, respectively. When using shielder, it shows 2.27 μSv/h, 1.34 μSv/h, and 1.13 μSv/h in 100, 150, and 200 cm on chest. On abdomen, the measured dose rates were 9.83 μSv/h, 5.15 μSv/h, and 3.18 μSv/h in 100, 150, and 200 cm, respectively. When using shielder, it shows 2.60 μSv/h, 1.75 μSv/h, and 1.23 μSv/h in 100, 150, and 200 cm on abdomen. Transmittance was increased as the distance was expanded.

As the distance was further, the radiation dose were reduced. When using shielder, the dose were reduced as one-forth of without shielder. The Radio technologists are exposed of radioactivity and there were limitations on reducing the distance with Therefore, the proper shielding will be able to decrease radiation dose to the technologists.

Key Words: PET, Shielding, Dose rate

Ⅰ. Introduction

From diagnosis to treatment and development of radiation equipment and an increase in health diagnosis, the scope of its business has expanded, the radiation field is increasing rapidly.

Accordingly, the frequency in which workers were exposed to radiation increases, and to radiation workers

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from exposure in care is important to the fore[1]. he energy of the radiation irradiated to mammalian cells ionizing radiation to be faulted radiation is irradiated to the human body is absorbed by the tissue, by interaction with substances or radiation sensitivity to radiation, the tissue is impaired tissue I induce[2,3,4].

Therefore, it is necessary when using the radiation, examine the radiation dose of at least affected less human body, to obtain the maximum benefit, the harm caused by the radiation exposure of radiation related workers and patients it is necessary to prevent, to perform thorough safety management to radiation[5]. Nuclear medicine can be divided in vivo test and in vitro test mainly. The in vivo tests, ^{99m}Tc labeled compounds to cover a check on the whole body bone scan, kidney scan, cardiac scan and brain scan. In addition, positron emission tomography examination using positron: there is a (Positron Emission Tomography, PET). The in vitro test, and the like radiation immunoassay typically. Before being administered to a patient radioisotope in the body examination, a radioactive isotope is the radiation source. But whole body of the patient is the source of radiation after administration[6]. In nuclear medicine, external dose rate due to radiation emitted from the patient, is an important indicator to recognize the extent of exposure to the radiation workers. External dose rate is present in the nuclear medicine laboratory. It has been believed that this and subjected to exposure is universal. Positron emission tomography equipment is installed for the first time in Korea in 1995, Seoul and country spread rapidly after the recent installation of PET is increasing rapidly. In addition, PET examination number was increased further to the realization of fusion PET image fitted with a computer tomography apparatus(Computed Tomography, CT). Thus, the use of positron−emitting radionuclide ^{18}F−FDG for use in PET examination is now increasing rapidly. Positron−emitting radionuclide emits gamma rays of 511 keV. So, radiation exposure of workers has increased compared to ^{99m}Tc of 140 keV existing. Therefore, efforts to reduce exposure dose is required[8,9]. Radiation protection activities, or those that are external to the human body, the radiation from the planning of external exposure and an intake of radionuclides inside the human body for internal exposure is classified into two. For radiation protection of external exposure, time, there is a law of three important distance, of shielding[10]. In this study, the PET examination, is measured external dose rate constant distance from the patient, and confirm the change of the dose rate according to the distance of the three principles of external exposure protection. Then, by using a shield, by analyzing the effect of the spatial dose distribution surrounding the patient and the change in the external dose rate, and is about to become useful for exposure control for radiation workers.

Ⅱ. Methods and Results

1 Patient Information

Have been in patients of 10 who came to our hospital for the PET/CT examination the average age of the target was 47.7 ± 6.6 years old.

Average height of the patients was 165.5 ± 3.8 cm, mean body weight was in patients with body weight similar at 65.9 ± 1.4 kg.

2. Radioactive Isotopes

$H_2{}^{18}O$ target cyclotron from (Cyclotron): 2 to 18F generated (p,n) in ^{18}F nuclear reaction ^{18}O−was synthesized (^{18}F−FDG) [^{18}F]−fluoro−2−deoxy−D−glucose, is used for inspection were. The nature of the 18F is the same as(Table 1).

Table 1. Property of ^{18}F.

Half-life (mim)	Decomposition method	Eβ −max [keV]	In the water maximum range(mm)	Maximum Specific activity (GBq/mmol)[Ci/mmol]
109.7	B+(97%)	635	2.4	6.3 · 107 (1.7 · 106)
	EC(3%)			

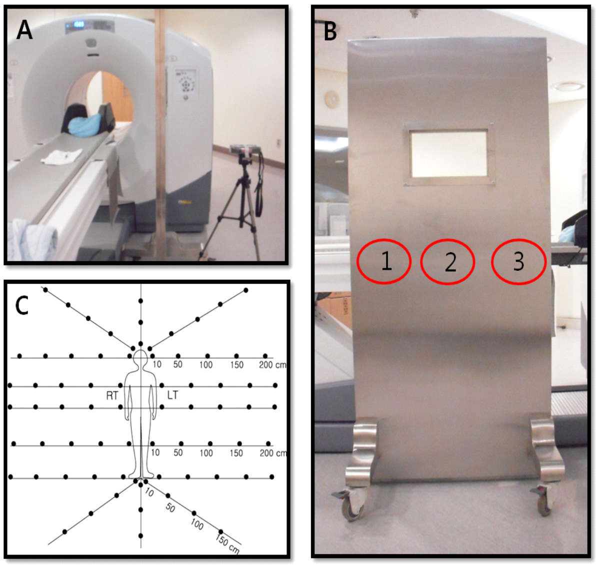

Fig. 1 Point source located in the middle of the table, and then to install a lead mobile protect were measured (A). Lead mobile protect is 900 x 1800 mm 10 T, lead equivalent 2.4 Pb portable radiation shielding. Measurement Location is 1, 2, 3 areas (1. Left part 2.Center part 3.Right part) (B). Schematic representation of measurement point of the external dose rates (C).

3. Test Methods

1) Impact assessment of the scattered radiation To confirm the effects of scattered radiation, after being positioned in the center of the table dotted ¥199.8 MBq, established a removable radiation shield, and 100 cm part left of the removable radiation shield, center, and right, I was measuring a total of 12 lines in the dose rate, 200 cm 150 cm. Height measurements were performed at the same height as the point source(Fig. 1.A, B).

2) Measurement of patient dose rate

After injection of ^{18}F–FDG 5.18 MBq/kg, was laid on the table after one hour, when the dose is stable part of the height of the gonads from the bottom, was measured once immediately. Were to look urine before lie on the table in order to minimize the radiation dose of urine. Before installing a removable radiation shield, was measured at the 10 cm, 50 cm, 100 cm, 150 cm, 200 cm from the position the head, chest, abdomen, knees, toe–side.

After installation of the radiation shield which is convenient for carrying around immediately after the measurement, by measuring the dose rate of the distance, 100 cm 150 cm, 200 cm in part head and chest, abdomen, and it was confirmed external dose rate (Fig. 1. C).

4. Equipment

PET/CT device was used PET/CT Discovery 600 (GE Healthcare, Milwaukee, WI, USA). External dose rate measuring device was used FH–40 GL (Thermo Scientific, USA) Using 900 x 1800mm, 10 T, the equipment 2.4 Pb removable year equivalents in the shield.

5. Methods of analysis

For the measurement of the scattered radiation, and was subjected to analysis of variance according to the distance for each location.

It has drawn equal dose curve obtained when the shielding with the absence of the lead shield, were subjected to correlation analysis between groups of two with respect to, 100 cm 150 cm, 200 cm (SPSS Ver. 12). Further, in order to calculate the transmittance of lead, was placed in a 50 cm lead, and the transmittance was measured for each lead, 100 cm 150 cm, 200cm.

Lead transmittance (%) prior to the installation of the prenetrating dose of lead ‘At’ said the lead after the installation of the penetrating dose ‘Ap’ is called. This will to can be calculated[10].

$$Lead\ \ Trasmit\tan ce\ \ (\%) = \frac{Ap}{At}\ X\ \ 100$$

Ⅲ. Results

1. Measurement of the dose rate by the measurement position of the shield

Median was higher at 100 cm in the measurement of scattered radiation using a point source. The 150 cm, measurements of left and right was high. In addition, there was little difference in the 200 cm (Fig. 2).

The measurement position corresponding to a respective distance, there was no significant difference $p > 0.05$.

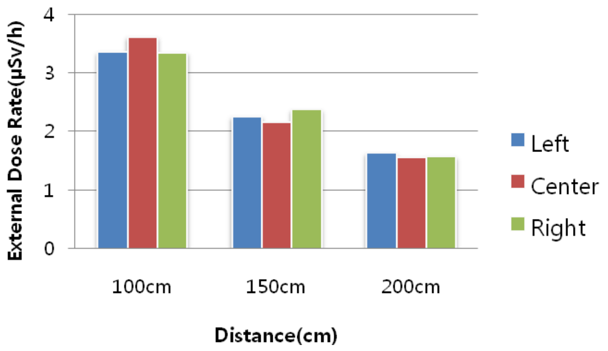

Fig. 2 Scatter dose measurements using a point source in the median of 100 cm and 150 cm high at the left and right sides were measured. In addition, the difference was not 200 cm.

2. Changes in the dose rate due to the distance

Part of the head is the highest and 105.40 μSv/h at a distance of average 10 cm, it was lowest with 12.49 μSv/h and 15.85 μSv/h from the part of the foot. Dose rate similar parts head, chest, abdomen is measured at a distance of 200 cm, a relatively low dose rate was measured at the knee portion, of the foot (Table 2).

Table 2. Dose rate measured by distance.

Unit :μSv/h

	10cm	50cm	100cm	150cm	200cm
Head 90°	95.49±9.26	21.14±4.16	9.1±0.91	4.16±0.8	2.66±0.49
Head 45°	90.88±7.4	22.91±5.7	8.84±0.87	3.68±0.39	2.21±0.58
Head	105.4±9.91	24.51±4.07	9.56±1.71	5.23±0.58	3.4±0.31
Chest	76.93±6.18	23.72±2.72	8.54±0.73	4.95±0.73	3.44±0.62
Abdomen	74.56±3.81	19.68±2.61	9.83±1.62	5.15±1.01	3.18±0.35
Knee	39.96±4.41	10.03±1.30	6.68±1.01	3.81±0.37	2.61±0.27
Foot	15.85±1.22	6.55±0.71	4.14±0.38	3.03±0.32	2.39±0.21
Foot 45°	13.53±2.38	5.26±0.75	2.73±0.34	2.08±0.23	1.39±0.2
Foot 90°	12.49±1.18	3.45±0.25	2.01±0.36	1.3±0.4	0.73±0.34

Dose of 1/2.57 1/4.51 – the distance to 50 cm from 10 cm accumulates on average decreased. Depending on the measurement site, 200 cm of 10 cm, was 1/6.63 – 1/40.9 (Table 3).

Table 3. Comparison of change distance for 10cm.

	10cm/50cm	10cm/100cm	10cm/150cm	10cm/200cm
Head 90°	4.51	10.49	22.95	35.89
Head 45°	3.96	10.28	24.69	40.98
Head	4.3	11.02	20.15	31
Chest	3.24	9	15.54	22.36
Abdomen	3.78	7.58	14.47	23.44
Knee	3.98	5.98	10.48	15.31
Foot	2.41	3.82	5.23	6.63
Foot 45°	2.57	4.95	6.5	9.7
Foot 90°	3.62	6.21	9.6	17.1

Dose of 1/2.00 1/2.77 – accumulated in the 100cm from 50 cm is reduced, the dose of 1/3.78 – 1/10.36 the distance to 200 cm from 50 cm accumulates is reduced. Reduction of dose due to the change in the distance and measured dose of 100 cm is 1/1.31 – 1/4.00, dose of 1/1.26 1/7.80 – has decreased in the comparison of the dose, 200 cm 150 cm (Table 4).

Table 4. Comparison of change distance for 50, 100, 150 cm.

	50cm/100cm	50cm/150cm	50cm/200cm		100cm/150cm	100cm/200cm	150cm/200cm
Head 90°	2.32	5.08	7.94	Head 90°	2.18	3.42	1.56
Head 45°	2.59	6.22	10.36	Head 45°	2.4	4	1.66
Head	2.56	4.68	7.2	Head	1.82	2.81	1.53
Chest	2.77	4.68	7.12	Chest	1.72	2.48	1.43
Abdomen	2	3.82	6.18	Abdomen	1.9	3.09	1.61
Knee	1.5	2.63	3.84	Knee	1.75	2.55	1.45
Foot	1.58	2.16	2.74	Foot	1.36	1.73	1.26
Foot 45°	1.92	2.52	3.78	Foot 45°	1.31	1.96	1.49
Foot 90°	1.71	2.65	4.72	Foot 90°	1.54	2.75	1.78

3. Changes in the dose rate due to the shield

Using a mobile radiation shield for the portion of the head with the highest dose rate, chest, abdomen, and measured by, 200 cm 100 cm, 150 cm. As a result, 3.40μSv/h was measured from 200 cm, 5.23μSv/h from 150 cm, 9.56μSv/h from the shield 100 cm from all parts of the head. After the shield, 1.27μSv/h was measured from, 200cm 1.67μSv/h from, 150cm 2.24μSv/h from 100cm. 100cm from the shielding, but significant differences before and after ($p < 0.05$), 150 cm and 200 cm there was no significant difference in the ($p > 0.05$). On the part of the chest, 3.44μSv/h was measured from 200 cm, 4.90μSv/h from 150 cm, 8.54μSv/h from the shield all 100 cm. After the shield, 1.13μSv/h was measured from 200 cm, 1.34μSv/h from 150 cm 2.27μSv/h from 100cm. 100cm from the shielding, but significant differences before and after ($p < 0.05$), 150 cm and 200 cm there was no significant difference in the ($p > 0.05$). On the part of the abdomen, 3.18μSv/h was measured from 200 cm, 5.15μSv/h from 150 cm, 9.83μSv/h from the shield all 100 cm. After the shield, 1.23μSv/h was measured from 200 cm, 1.75μSv/h from 150 cm 2.60μSv/h from 100 cm. 100 cm from the shielding, but significant differences before and after ($p < 0.05$), 150 cm and 200 cm there was no significant difference in the ($p > 0.05$) (Fig. 3. A, B, C).

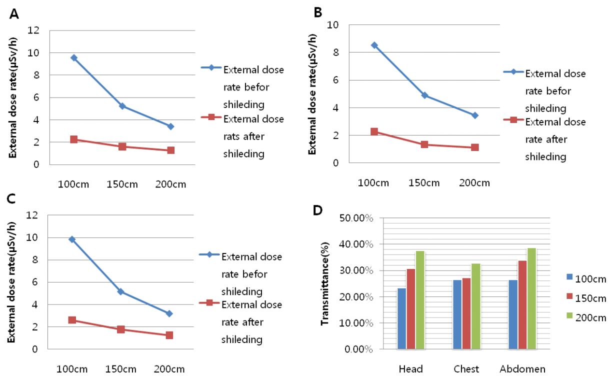

Fig. 3 The head, chest and abdomen shielded from 100, 150, 200 cm at the before and after dose were measured. Each dose was reduced in the area after shielding. In addition, the increased transmittance with increasing distance. Head part to external dose rate shielding ago, after the external dose rate (A) Chest part to Shielding to ago, after the external dose rate (B) Abdomen part to Shielding to ago, after the external dose rate (C) Transmittance of distance and area (D).

The distance from the head portion, the chest, the abdomen increases result of measuring the transmittance of lead, the transmittance is increased (Fig. 3. D).

The equal dose curve from head, chest and abdomen was show for high-dose as before shielded and that the head, chest and abdominal was show for dose decreased as after shielding(Fig. 4. B, C).

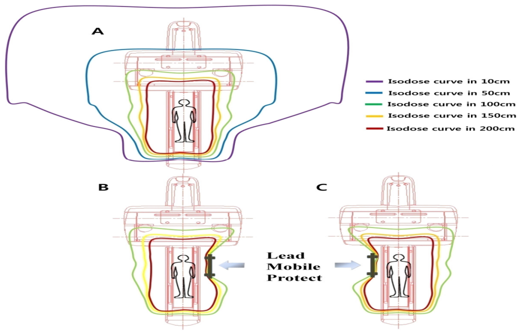

Fig. 4 The equal dose curve from head, chest and abdomen was show for high-dose as before shielded and that the head, chest and abdominal was show for dose decreased as after shielding. Equal dose curve of external dose rates from patient. Equal dose curve ago shielding (A) Equal dose curve after 100 cm, 150 cm, 200 cm shielding(Left) (B) Equal dose curve after 100 cm, 150 cm, 200 cm shielding(Right) (C).

Ⅳ. Disccution

Management of radiation exposure of workers has emerged as important to the increase in the development and use of radiation devices, for medical use is increased, the exposure of the duties of the workers is also increasing gradually. The international radiation protection committee(International Commission on Radiological Protection : ICRP) which was formed in 1928, within a range of a 100 mSv in five years from 50 mSv year, it is recommended a dose limit to 20 mSv per year up to occupational exposure [11]. Nuclear medicine scans is $^{99m}TcO_4$ cover compounds combined with DMSA, kidney scan, HMPAO using brain scans, and bone with the MDP, HDP, $^{99m}TcO_4$ cover compounds-induced inflammation using a screening tests and ^{67}Ga, ^{201}Tl myocardial infarction using scan, PET scan using ^{18}F-FDG. Energy(140 keV) and suitable half-life(6 hours), usually in the in vivo tests, the physical condition of the radiopharmaceutical for use in nuclear medicine is suitably 80 ~ 500 keV. Then, using the gamma rays of high energy resolution of the image is reduced, the detection efficiency is reduced in the measurement of the coefficient. Conversely, if it is a low-energy gamma rays, the radiation absorbed in the tissue is increased, the detection efficiency is reduced measurement becomes difficult. $^{99m}TcO_4$ is widely used in nuclear medicine energy is short, since the release of low gamma radiation.

Radioisotopes typically used for PET examination, using ^{18}F produced by cyclotron. When the positron emitting, lost all the kinetic energy of the positron(640 keV), arresting around and combine with electrons, radioactive physical properties of 18F emit annihilation radiation(gamma ray 511 keV) emitted in the direction of 180˚.

Recently a dose of radiation workers is nuclear medicine 0.32 ± 0.41 mSv, cardiovascular 0.29 ± 0.6 mSv, video of 0.20 ± 0.47 mSv, oncology and 0.11 ± 0.25 mSv, other departments 0.13 ± 0.37 mSv and nuclear medicine dose showed[12]. In addition, the annual average radiation dose nuclear medicine Radiological technologists is 5.07 ± 3.13, Dose of the gamma camera worker is 4.15 ± 2.26 mSv, Irradiation dose of PET worker is 7.41 ± 3.04 mSv. Dose of PET workers had the highest. Gamma camera laboratory uses a relatively low gamma energy of 140 keV by performing a test by labeling the labeled compound $^{99m}TcO_4$ most. The PET examination room, in order to use the relatively high annihilation radiation of 511 keV generated from the positron-emitting radionuclide, radiation exposure is increased. In vitro tests administered to patients with a radioactive isotope, radioactive isotopes radiation sources before, but after the radioactive isotope, dose of whole body radiation of the patient. Patients to radiation sources from the patient administration of radioactive isotopes, which moment important is external radiation protection from the environment. Three principles of radiation external protection may be described separately "time, distance, shielding". Dose is accumulated as the time of radiation exposure is prolonged. Dose person at the location of the constant dose rate received is directly proportional to the time it has remained in its place. That is, because it is a "Dose = dose rate x time" dose also decreases by reducing the radiation working time. Reduction of working time is a more important work dose rate is high.

Also increase the distance and source is the radiation exposure from external source, inversely proportional to the square of the distance. To double the distance from the source, x-ray dose rate to 4-1, three times, and has reduced to 1/9. To make is important to ensure regular intervals if necessary, to keep the intervals of a shield by putting the shield sometimes difficult. For penetrating power is large, shielding of gamma rays, using high density, lead, concrete and iron. In this study, it was confirmed the change in dose rate due to the shield with changes in dose rate corresponding to the distance. Part of the head was higher than the other portions in 105.4 µSv/h when it was measured at a distance of 10 cm. And, part of the chest was 74.56 µSv/h, part of the abdomen was 76.9 µSv/h. Most of the measures are higher than the measurement is the chest portion of the abdomen parts, but the two measures were part of the abdomen from the chest part. The reason is that the influence of urine in the bladder for patient it's just urine tests before measurement began, the majority of radiopharmaceuticals as urine excretion remained in the bladder because they drink no more radiation measurements for that feed. In parts of the feet and head, there was a difference of 1/1.42 ~ 1/6.67 about dose rate. Dose rate depending on the measurement site, the change in distance was 1/6 to 1/40. In addition, the dose rate is the most highly came out of the head, chest, abdominal part is 100 cm, 150 cm, 200 cm the average dose is similar. Depending on the distance between the measurement site of the shield using a point source, is 100 cm, the middle portion is measured higher than the right and left. Under the influence of scattered radiation, better at both ends of the shield was measured higher than the center at 150 cm. No difference was observed in the 200 cm or more, there was no significant difference in accordance with the measurement portion of the shield.

Placed at a distance of 50 cm the shield was measured with, 200 cm 100 cm, respectively, 150 cm. On average 100 cm before the head shielding 9.56 μSv/h, 150 cm, 200 cm 5.23 μSv/h at 3.4 μSv/h, and on average 2.24 μSv/h 100 cm after shielding the 150 cm, 200 cm 1.61 μSv/h at 1.27 μSv/h, as the distance increased, there was no significant difference in effectiveness for shielding. In addition, when 100 cm from the head part of the transmittance 23.43 % 30.86 % from 150 cm, 200 cm distance to 37.6 % increases in transmittanceis increased. Distance there is a shielding effect of 76 % when 100 cm increases, the shielding effect is reduced.The distance increases, the dose rate is reduced, the effect of the shield is lowered.

Ⅴ. Conclusion

In defense of external exposure, distance, time, there are three laws of shielding.

In this study, it was confirmed the change in dose rate depending on the distance and shielding. Dose rate becomes lower as the distance away. Value measured at 100 cm than the value that is measured at 10cm decreased to 1/10 or less head dose rate was measured highest.Is measured at a dose rate the highest part of the head, dose rate was lower as it goes part of the foot. Further, if it is a shield, the dose rate is lower than when it is not in the shielding. There was a significant difference at 100 cm, but there was no significant difference in, 200 cm 150 cm. In order to reduce the exposure, that or far distance from the radiation source, using an appropriate shield will help reduce exposure. However, nuclear medicine, for injecting a radioactive isotope into a patient, the patient becomes radioactive source. Since, the workers are inspected laboratories, because it can not be farther the distance from the patient, not only radiation exposure increases. Therefore, it will be possible to grasp the flow line of the radiation workers, by using a suitable shield to reduce the radiation exposure of the radiation workers.

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•국문초록

PET-CT 검사에서 방사선 종사자 피폭선량 저감에 대한 방안 연구

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양전자 방출핵종은 511 keV의 감마선을 방출하기 때문에 기존 140 keV의 ^{99m}Tc에 비해 종사자의 방사선 피폭의 증가로 피폭선량 저감을 위한 노력이 요구된다. 본 연구는 환자에게로부터 일정거리에 따른 선량률 변화를 확인하고 차폐를 이용하여 외부선량률의 변화를 알아보았으며 환자 주변의 외부선량 분포에 대한 영향을 분석하여 방사선 종사자의 피폭 관리에 도움이 되고자 하였다.

10 명의 환자를 대상으로 하였으며 평균연령은 47.7 ± 6.6 세였다. 환자의 키는 평균 165.5 ± 3.8 cm, 몸무게 평균은 65.9 ± 1.4 kg 으로 비슷한 몸무게의 환자를 대상으로 하였다.

머리, 가슴, 복부, 무릎, 발끝 쪽의 위치에서 10 cm, 50 cm, 100 cm, 150 cm, 200 cm 위치에서 측정하였고 측정 후에 즉시 이동형 방사선 차폐체을 설치한 후 머리와 가슴, 복부 부분에서 100 cm, 150 cm, 200 cm 거리에서 선량률을 측정하였다. 거리에 따른 선량률 변화와 차폐 전, 후의 투과율을 구하였다.

평균 10 cm 거리에서는 머리 부분이 105.40 μSv/h 로 가장 높게 나타났으며 발 부분에서 15.85 μSv/h로 가장 낮게 나타났다. 200 cm 거리에서는 머리, 가슴, 복부 부분에서 비슷한 선량률이 나타났다. 머리 부분에서 차폐 전 100 cm에서 9.56 μSv/h, 150 cm에서 5.23 μSv/h, 200 cm에서 3.40 μSv/h로 나타났으며 차폐 후에는 100 cm, 150 cm, 200 cm 에서 각각 2.24 μSv/h, 1.67 μSv/h, 1.27 μSv/h로 측정되었다. 가슴 부분에서 차폐 전 100 cm에서 8.54 μSv/h, 150 cm에서 4.90 μSv/h, 200 cm에서 3.44 μSv/h로 나타났으며 차폐 후에는 100 cm, 150 cm, 200 cm 에서 각각 2.27 μSv/h, 1.34 μSv/h, 1.13 μSv/h로 측정되었다. 복부 부분에서 차폐 전 100 cm에서 9.83 μSv/h, 150 cm에서 5.15 μSv/h, 200 cm에서 3.18 μSv/h로 나타났으며 차폐 후에는 100 cm, 150 cm, 200 cm 에서 각각 2.60 μSv/h, 1.75 μSv/h, 1.23 μSv/h로 측정되었다. 투과율은 거리에 따라 증가함을 알 수 있었다.

거리가 멀어질수록 선량율이 낮아지는 것을 확인할 수 있었으며 차폐를 하였을 경우 차폐를 하지 않았을 때보다 1 / 4 정도 더 낮아지는 것을 확인할 수 있었다. 검사를 진행하는 근무자는 환자와의 거리를 멀리 할 수 없기 때문에 방사선 피폭이 증가할 수밖에 없다. 따라서 적절한 차폐를 한다면 방사선 종사자의 방사선 피폭을 줄 일 수 있을 것이다.

중심 단어 : 양전자방출, 차폐, 선량율