Journal of the Korea Convergence Society
Vol. 12. No. 4, pp. 87-94, 2021

ISSN 2233-4890 / eISSN 2713-6353
https://doi.org/10.15207/JKCS.2021.12.4.087

Analysis of Radiation Fusion Shielding Performance of Ytterbium Oxide, a Radiation Impermeable Substance

Seon-Chil Kim
Professor, Department of Biomedical Engineering, School of Medicine, Keimyung University

방사선 불투과성 물질 산화이테르븀(Ytterbium oxide)의 방사선 융합 차폐성능 분석

김선칠
계명대학교 의용공학과 교수

Abstract While the shielding substances of radiation shields in medical institutions are beginning to be replaced by environmentally friendly materials, radiation protection according to the shielding properties of environmentally friendly substances is becoming an important factor rather than the existing lead shielding properties. Tungsten and barium sulfate are representative shielding materials similar to lead, and are made in sheets or fiber form with eco-friendly materials. Ytterbium is an impermeable material used as a fluorine compound in the dental radiation field. This study aims to evaluate the shielding performance in the x-ray shielding area by comparing the shielding properties of ytterbium by energy band and that of existing eco-friendly materials. When three types of shielding sheets were fabricated and tested under the same process conditions, the shielding performance of the medical radiation area was about 5 % difference from tungsten. Furthermore, shielding performance was superior to barium sulfate. In the cross-sectional structure of the shielding sheet, there was a disadvantage that the arrangement of particles was not uniform. Ytterbium oxide showed sufficient potential as a medical radiation shielding material, and it is thought that it can improve the shielding performance by controlling the particle arrangement structure and particle size.

Key Words : Ytterbium oxide, Tungsten, Barium sulfate, Radiation Fusion Shielding, Linear absorption coefficient

요 약 의료기관의 방사선 차폐체의 차폐물질이 친환경소재로 변화되면서 기존 납의 일반된 차폐특성보다 차폐물질의 특성에 따른 방사선 방어가 중요한 요소로 대두되고 있다. 납과 유사한 차폐물질로 대표적인 텡스텐과 황산바륨은 친환경 소재로 시트나, 섬유 형태로 제작되어 사용되고 있다. 이테르븀은 치과 방사선영역에서 불투과성 물질로 불소화합물로 사용되었으며, 에너지대별 차폐특성과 기존 친환경소재의 차폐특성과 비교하여 x-선 차폐영역에서 차폐성능을 평가하고자 한다. 동일한 공정과 조건하에 세 종류의 차폐시트를 제작하여 실험하였으며, 의료방사선 영역에서 텅스텐과 약 5 % 차폐성능 차이가 나타났으며, 황산바륨보다 우수한 차폐성능을 보였다. 차폐시트의 단면 구조에서는 인자의 배열이 일정하지 못하는 큰 단점을 보였다. 따라서 산화이테르븀은 의료방사선 차폐물질로 충분한 가능성을 보였으며, 입자배열 구조와 입자크기 조절로 차폐성능을 향상시킬 수 있을 것으로 사료된다.

주제어 : 산화이테르븀, 텅스텐, 황산바륨, 방사선 융합 차폐, 선흡수계수

*This work was supported by Radiation Technology R&D program through the National Research Foundation of Korea funded by the Ministry of Science and ICT(2020M2C8A1056950).
*Corresponding Author : Seon-Chil Kim(chil@kmu.ac.kr)
Received March 3, 2021
Revised March 26, 2021
Accepted April 20, 2021
Published April 28, 2021

1. Introduction

Most of the radiation shields in medical institutions use lead as a material[1]. Since lead has a high atomic number, it has a very high probability of interaction with the incident energy of radiation, making it suitable as a radiation absorbing material. In addition, it is widely used as a single material and a composite material due to its excellent workability and economy[2,3]. However, lead poses a risk as a radiation shielding material due to human poisoning, contamination of the manufacturing process, and difficulty in disposal[4,5]. As alternative substances, there are tungsten, bismuth oxide, barium sulfate, etc. as raw materials that can be easily commercialized, and recently, such environment-friendly materials have been attracting attention[6].

Most of the shields used in medical institutions are aprons, gloves, and shielding cloths. Recently, many types of clothing such as hats and scarves have been commercialized [7]. Most of these products are used as shielding tools to ensure the activity of medical staff in the radiation generating area. The balance between shielding performance and user activity is very important, and from this point of view, when used for shielded garments, it must be light in weight and adjustable in thickness.

When making aprons, the shield is mainly made in the form of sheets or fibers. However, in order to show a shielding rate equivalent to that of lead, the fiber must be manufactured with a high thickness, and the sheet exhibits a shielding rate equivalent to that of lead, but the satisfaction with the thickness is still not high[8]. This can be mostly a limiting factor due to the use of substances such as lead, tungsten, barium sulphate and the like. Therefore, research on new shielding materials is urgent in order to meet the requirements for light weight and thin film required by medical institutions. The new shielding material requires a single material such as the existing material, or a composite material that is a mixture of several materials, or a composite material with a physical layered structure.

The most preferred substance in a single material is tungsten. Tungsten has an atomic number of 74 and a density of 19.25 g / cm^3 and is known as an effective alternative to lead. In addition, it is most often used as a material for a thin film shielding film for the purpose of shielding cosmic radiation or medical radiation, and is used in the form of a sheet by mixing with a polymer material[9]. However, although tungsten has excellent shielding performance, it lacks economy and workability, so it is difficult to manufacture various forms with a single material, and it is mainly used as a powdered mixed material.

Barium sulfate, which is represented as a biocompatible material, is used as a radiation absorbing material for materials inserted into the human body because it is harmless to the human body. In addition, it is mainly used as a material for a radiation absorption indicator[10]. However, barium sulfate is also difficult to use in a wide range because the radiation absorption effect is not large per unit area and the absorption effect is different for each energy group. Therefore, it is mainly used in a specific energy range[11]. As such, radiation shielding materials have various characteristics, so it is necessary to use a shielding body suitable for them.

In this study, the shielding performance of ytterbium, which is used as a dental material, is compared with barium sulfate and tungsten to test the possibility of the shielding material. Ytterbium has an atomic number of 70 and a density of 6.90 g/cm^3, which is similar to tungsten, but it is very inexpensive, so it can be said to have economic feasibility when fabricated as a radiation shield[12]. Therefore, it is intended to evaluate the shielding performance of ytterbium and the possibility of shielding materials using the radiation energy used in medical institutions. In addition, after comparing with the tungsten and barium sulfate shielding sheets manufactured through the same manufacturing process, and examining the cross-sectional particle arrangement, the compatibility with the polymer material is evaluated to present the validity of the medical radiation shielding material.

2. Materials and methods

If radiation reacts with its constituent atoms or atomic nuclei while passing through a substance or medium, the intensity of the radiation is attenuated. The space of the medium is a shielding body, and direct or indirect shielding effects can be obtained due to the shielding material corresponding to the constituent material. Therefore, the degree of attenuation for the intensity of radiation energy per unit distance traveled within the material is expressed as a linear absorption coefficient (μ), and can be expressed as Eq 1 [13].

$$\mu = \frac{1}{\chi} ln \frac{N_0}{N} \quad \text{Eq. 1}$$

In this equation, χ is the thickness of the shield, N is the radiation dose when there is a shield between the detector and the radiation generator, and N_0 is the radiation dose without the shield. Therefore, the radiation shielding effect increases as the structure in which radiation photons passing through the shielding body can interact like electrons or nuclei of the shielding material and the inherent linear absorption coefficient of the shielding material are higher[14].

In this experiment, a shielding sheet was produced using ytterbium oxide, and a shielding sheet was fabricated using tungsten and barium sulfate through a manufacturing process under the same conditions in order to compare the shielding characteristics with existing eco-friendly radiation shields. High-density polyethylene(HDPE) was used as the polymer material mixed for stirring with the shielding material in the manufacturing process[15]. The HDPE used in this study has a molecular weight of more than 4 million and a density of 0.91 g/cm³ and is highly used mainly as a disposable plastic product due to its excellent strength.

The shielding material powder particles were micro-sized, and dried at 70°C for 12 hours before use. Since a solid polymer is used, a casting solution was made using N-dimethylformamide (DMF, 99.5%) as a solvent. DMF was dissolved with HDPE in a stirrer at a ratio of about 10 wt%, and the shielding material powder was added to the finished casting solution, and the shielding material particles were dispersed by stirring at 5000 rpm. The plasticizer used to remove the porosity inside the shielding sheet was Diisononyl phthalate (DINP), and 0.85~0.95wt% was used[16]. To maintain the uniform shielding performance of the final casting solution, a filter was used to remove foreign substances, and then a bubble removal operation was performed. The final shielding sheet was finished with a calendar process of compression molding, and the size of the final shield sheet was 100 mm × 100 mm, which is the same as that shown in Fig. 1.

Fig. 1. Shielding sheet made using three materials for comparison (A: Ytterbium oxide shielding sheet, B: Barium sulfate shielding sheet, C: Tungsten shielding sheet)

In this experiment, a radiation shielding experiment was prepared as shown in Fig. 2 to compare and evaluate the shielding performance of the three shielding materials. The three types of sheets had the same size and thickness, but the weights differed slightly depending on the mixing amount of the shielding material. The particle size and dispersibility of the shielding material were observed using an opti-cal microscope (FESEM; field-emission scanning electron microscope, Hitachi, S-4800) through thin-film intercepts of the shielding sheet. The shielding rate was tested 10 times using an X-ray generator (Toshiba E7239, 150kV-500mA, 1999, Japan), and the average value was used. The dose detector used was DosiMax plus 1 (2019.iba Dosimetry.Corp.) and used after the inspection and calibration.

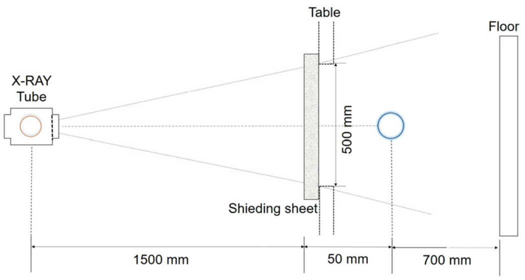

Fig. 2. Evaluation of Radiation Shielding Performance of Shielding Sheets

To evaluate the shielding performance of the shielding sheet produced in the experiment, the shielding rate was calculated as Eq 2[17].

The X-ray energy generation conditions were tested by changing the tube voltage based on a tube current of 200 mA and a exposure time of 0.1 seconds. k is the exposure dose measured when there is a shielding sheet between the X-ray beam and the detector, and k_0 is calculated as the exposure dose measured when there is no shielding sheet between the X-ray beam and the detector.

X-ray shielding rate(%)

$$= (1 - \frac{k}{k_0}) \times 100 \quad \text{.......... Eq. 2}$$

k_0 = Incident dose(mR),

k = Transmitted dose(mR)

3. Results

As a result of fabricating a sheet form through the same manufacturing process using shielding material powders of ytterbium oxide, tungsten, and barium sulfate, the three shielding sheets have the composition shown in Table 1. There was no difference in appearance and composition ratio, but there was a difference in the particle packing of the shielding material and the weight per unit area. In general, the mixability of barium sulfate was excellent, followed by the mixability of ytterbium oxide. Sheets made of ytterbium oxide had the lowest weight per unit area. Through this, it is expected that the blendability of the base material HDPE and the polymer material will proceed without much difference from the base material.

Table 1. Fabrication composition of radiation shielding sheet

Item	Value		
	A	B	C
Sheet structure	Single structure		
Shielding material	Ytterbium oxide	Barium sulfate	Tungsten
Mixing ratio (Polymer:Shielding material)	1:3		
Sheet weight (kg/m²)	1.3	1.6	1.5
Sheet thickness (㎜)	2±0.185		
Shielding material(g)	75.4	80.4	67.1

※ A: Ytterbium oxide shielding sheet, B: Barium sulfate shielding sheet, C: Tungsten shielding sheets

When comparing the cross-sectional images of the produced shielding sheet, it appears that the

Ytterbium oxide has a wide distance between particles (DBP) as shown in Fig. 3(a). Also, As shown in Fig. 3 (c), tungsten had the most stable cross-sectional structure. The porosity and pinholes observed in the cross-sectional structure are the most important factors that directly affect the shielding performance. When compared at the same magnification, it was observed that the size of the ytterbium oxide particles was large[18]. Unlike other materials, it seems that more observations are needed for the milling time and process of ytterbium oxide. In addition, if mass production is required in the future, it is expected that further studies on the stirring process will be needed for a stable particle arrangement structure.

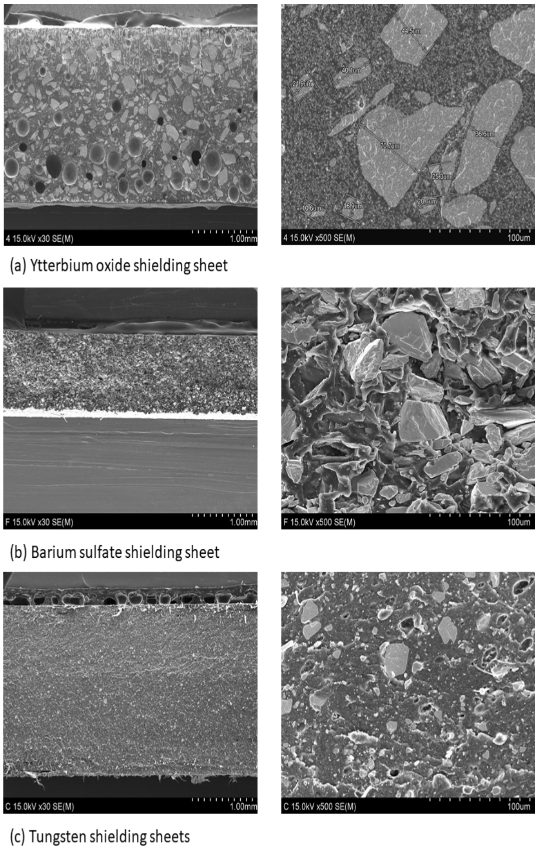

Fig. 3. Comparison of cross-sectional images of three types of shielding sheets

The shielding performance evaluation for the three shielding sheets is shown in Fig. 4. The shielding performance of the tungsten shielding material was the best, and there was a difference of about 5% from ytterbium oxide. Barium sulfate showed the lowest result. The sheets made of ytterbium oxide showed similar shielding performance and energy attenuation patterns as tungsten sheets.

In particular, barium sulfate was found to have some effect of shielding performance at high tube voltages, as previously used in high tube voltage fluoroscopy.

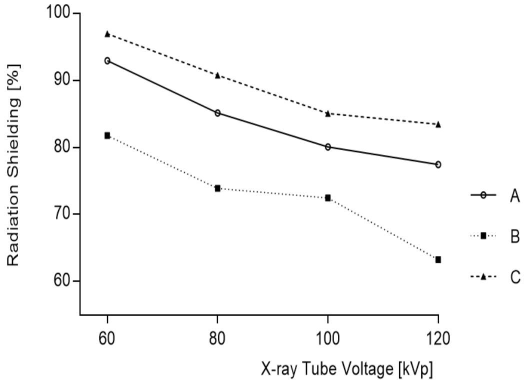

Fig. 4. Comparison of shielding performance by shielding material (A: Ytterbium oxide shielding sheet, B: Barium sulfate shielding sheet, C: Tungsten shielding sheets)

4. Discussion

Lead, which is widely used as a shielding material for medical institutions, is used as a shielding body of 0.25 mmPb and 0.50 mmPb based on the lead equivalent[19]. Ytterbium oxide, which is mainly used as an absorbing material in dental radiation, can be used as a medical radiation shielding material only if it meets this shielding performance. In this study, the shielding performance was evaluated whether ytterbium oxide could be used as a shielding material such as tungsten and barium sulfate, and the experimental results showed sufficient potential.

Ytterbium is known as a material that is not harmful to the human body as it is mixed with fluorine and used as a dental material[20]. Therefore, if the stability as an eco-friendly material is recognized and has a shielding performance similar to that of lead, it can be manufactured as a shield for human body protection.

Existing ytterbium was mainly used as a low-dose radiation shielding material and used as a coating material for the main shield[21]. In addition, there are cases where it was used as a contrast medium in nano form, which can be understood as evidence that it played a role as a material absorbing radiation from the main energy[22].

In this study, the shielding performance in the x-ray energy range was compared and analyzed with eco-friendly materials for the purpose of using it as a medical radiation shield. Ytterbium has a radiation absorbing performance similar to tungsten, and it can be effective if it is used in the form of a mixed or complex material rather than used as a single material. Existing studies have been conducted on materials with high radiation absorption in low-dose areas and materials with high absorption capacity in high-dose areas, and through this, appropriate shielding is possible according to the energy pattern, thereby effectively responding to the physical defense of medical personnel[23].

Conventional ytterbium is often used in dental procedures because of its impermeability to radiation, and is mainly provided in the form of fluorine compounds[24]. The dental radiation area is mainly a low-dose energy area, which can present sufficient radiation absorption properties.

In this experiment, there are limitations in the manufacturing process conditions of the shielding sheet, such as the failure to present the shielding performance for each effective energy, and the use of additives in the relationship between the properties of each material and the process technology.

Through this study, the radiation shielding effect of ytterbium oxide was proved, and although it did not reach the shielding performance of tungsten, it suggested more effective shielding performance than barium sulfate of the same price range. It is expected that effective radiation shielding will be possible through mixing with other shielding materials in the future.

5. Conclusions

Ytterbium oxide showed consistent shielding performance in the radiation energy range used in the medical field. In addition, the shielding performance showed a difference of 5% from that of the tungsten shielding material, and was superior to that of barium sulfate. Therefore, it can be said that ytterbium oxide has sufficient potential as a material that can be used for the development of shields in medical institutions.

REFERENCES

[1] A. K. Singh, R. K. Singh, B. Sharma & A. K. Tyagi. (2017). Characterization and Biocompatibility Studies of Lead Free X-ray Shielding Polymer Composite for Healthcare Application. *Radiat. Phys. Chem. 138,* 9-15. DOI : 10.1016/j.radphyschem.2017.04.016

[2] H. A. Maghrabi, A. Vijayan, F. Mohaddes, P. Deb & L. Wang. (2016). Evaluation of X-ray radiation shielding performance of barium sulphate-coated fabrics. *Fibers and Polymers, 17(12),* 2047-2054. DOI : 10.1007/s12221-016-5850-z

[3] S. C. Kim. (2021). Prediction of Shielding Performance by Thickness by Comparing the Single and Laminated Structures of Lead-free Radiation Fusion Shielding Sheets. *Journal of the Korea Convergence Society, 12(1),* 105-110. DOI : 0.15207/JKCS.2021.12.1.105

[4] D. Adlienė, L. Gilys & E. Griškonis. (2020). Development and Characterization of New Tungsten

and Tantalum Containing Composites for Radiation Shielding in Medicine. *Nucl. Instrum. ethods Phys. Res. B, 467,* 21–26. DOI : 10.1016/j.nimb.2020.01.027

[5] S. C. Kim. (2018). Physical Properties of Medical Radiation Shielding Sheet According to Shielding Materials Fusion and Resin Modifier Properties. *Journal of the Korea Convergence Society, 9(12),* 99-106. DOI : 10.15207/JKCS.2018.9.12.099

[6] Nurul Z. Noor Azman et al. (2016). Effect of Bi2O3 particle sizes and addition of starch into Bi2O3–PVA composites for X-ray shielding. *Applied Physics A, 122(9),* 818-. DOI : 10.1007/s00339-016-0329-8

[7] M. K. Badawy, MAppSci, P. D. PhD, R. C. MBBS. PhD & O. F. MBBS. PhD. (2016). A Review of Radiation Protection Solutions for the Staff in the Cardiac Catheterisation Laboratory. *Heart, Lung and Circulation, 25(10),* 961-967. DOI : 10.1016/j.hlc.2016.02.021

[8] S. C. Kim & H. M. Jung. (2013). A Study on Performance of Low-Dose Medical Radiation Shielding Fiber (RSF) in CT Scans. *International Journal of Technology, 4(2),* 178-187. DOI : 10.14716/ijtech.v4i2.107

[9] N. J. AbuAlRoos, M. N. Azman, N. A. B. Amin & R. Zainon. (2020). Tungsten-based material as promising new lead-free gamma radiation shielding material in nuclear medicine. *Physica Medica. 78,* 48-57. DOI : 10.1016/j.ejmp.2020.08.017

[10] N. Aral, F. B. Nergis & C. Candan. (2015). An alternative X-ray shielding material based on coated textiles. *Textile Research Journal, 86(8),* 803-811. DOI : 10.1177/0040517515590409

[11] L. Seenappa, H. C. Manjunatha, B. M. Chandrika & H. Chikka. (2017). A Study of Shielding Properties of X-ray and Gamma in Barium Compounds. *Journal of Radiation Protection and Research, 42(1),* 26-32. DOI : 10.14407/jrpr.2017.42.1.26

[12] Y. Liu, J. Liu, K. Ai, Q. Yuan & L. Lu. (2014). Recent advances in ytterbium-based contrast agents for in vivo X-ray computed tomography imaging: promises and prospects. *Contrast Media Mol. Imaging, 9(1),* 26-36. DOI : 10.1002/cmmi.1537

[13] Y. S. Choi, I. S. Kim, S. Y. Choi & E. I. Yang. (2019). Fundamental Properties and Radioactivity Shielding Characteristics of Mortar Specimen Utilizing CRT Waste Glass as Fine Aggregate. *Journal of the Korea Institute for Structural Maintenance and Inspection, 23(1),* 163-170. DOI : 10.11112/jksmi.2019.23.1.163

[14] S. M. Midgley. (2004). A parameterization scheme for the x-ray linear attenuation coefficient and energy absorption coefficient. *Physics in Medicine & Biology, 49(2),* 307-325. DOI : 10.1088/0031-9155/49/2/009

[15] J. W. Shin et al. (2014). Polyethylene/boron-containing composites for radiation shielding. *Thermochimica Acta, 585(10),* 5-9. DOI : 10.1016/j.tca.2014.03.039

[16] S. E. Gwaily, H. H. Hassan, M. M. Badawy & M. Madani. (2002). Study of electrophysical characteristics of lead-natural rubber composites as radiation shields. *POLYMER COMPOSITES, 23(6),* 1068-1075. DOI : 10.1002/pc.10502

[17] N. Papadopoulos et al. (2009). Comparison of Lead-free and Conventional x-ray aprons for Diagnostic Radiology. *World Congress on Medical Physics and Biomedical Engineering, 25(3),* 544-546. DOI : 10.1007/978-3-642-03902-7_155

[18] Ali Basheer Azeez, Kahtan S. Mohammed, A. M. Mustafa Al Bakri, Hana Ihsan Hasan & Omar A. Abdulkareem. (2014). Radiation Shielding Characteristics of Concretes Incorporates Different Particle Sizes of Various Waste Materials. *Advanced Materials Research, 925,* 190-194. DOI : 10.4028/www.scientific.net/AMR.925.190

[19] J. P. McCaffrey, H. Shen, B. Downton & E. M. Hing. (2007) Radiation attenuation by lead and nonlead materials used in radiation shielding garments. *Medical physics, 34(2),* 530-537. DOI : 10.1118/1.2426404

[20] Neftali L. V. Carreño et al. (2012). YbF_3/SiO_2 Fillers as Radiopacifiers in A Dental Adhesive Resin. *Nano-Micro Letters, 4(3),* 189-196. DOI : 10.1007/BF03353713

[21] B. P. Fox, K. Simmons-Potter, J. H. Simmons, W. J. Thomes Jr., R. P. Bambha & D. A. V. Kliner. (2007). Investigation of radiation-induced photodarkening in passive erbium-, ytterbium-, and Yb/Er co-doped optical fibers. *Nanophotonics and Macrophotonics for Space Environments. 6713.* DOI : 10.1117/12.735212

[22] L. Jianhua et al. (2013). Large-Scale and Facile Synthesis of Biocompatible Yb-Based Nanoparticles as a Contrast Agent for In Vivo X-Ray Computed Tomography Imaging. *Current Topics in Medicinal Chemistry, 13(4),* 513-518. DOI : 10.2174/1568026611313040011

[23] G. Panuccio, R. K. Greenberg, K. Wunderle, T. M. Mastracci, M. G. Eagleton & L. Davros. (2011). Comparison of Indirect Radiation Dose Estimates with Directly Measured Radiation Dose for Patients and Operators during Complex Endovascular Procedures. *Journal of Vascular Surgery, 53(4),* 885–894.e1. DOI : 10.1016/j.jvs.2010.10.106

[24] F. M. Collares, F. A. Ogliari, G. S. Lima, V. R. C. Fontanella, E. Piva & S. M. W. Samuel. (2010). Ytterbium trifluoride as a radiopaque agent for dental cements. *International Endodontic Journal, 43(9),* 792-797. DOI : 10.1111/j.1365-2591.2010.01746.x

김 선 칠(Seon-Chil Kim) [정회원]

· 2003년 2월 : 고려대학교 의료정보기기학과 (공학석사)
· 2009년 2월 : 경북대학교 의료정보학과 (의료정보학박사)
· 2003년 3월 ~ 2015년 8월 : 대구보건대학교 방사선과 교수
· 2015년 9월 ~ 현재 : 계명대학교 의용공학과 교수
· 관심분야 : 방사선 차폐, 의료기기, 의료정보
· E-Mail : chil@kmu.ac.kr