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A Study on Effect of Layer Height and Nozzle Size of Radiation Shielding Production Using FFF Type 3D Printer

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ABSTRACT
The purpose of this study is to investigate and discuss the effect of the printing parameters of copper blend filament shielding by FFF.In order to improve the quality of metal blend filament printouts, it is necessary to understand the principles of 3D printers and to have an excellent combination of parameter settings of intrinsic factors and additional factors. Essential factors include the atomic number and density of the material, while additional factors include nozzle size, layer height, inner pattern, and fill density. Parametric study of product properties is an important subject for quality improvement. Appropriate adjustment of additional elements between parameters can improve output quality. Among them, in the case of a shield made with a 3D printer, the internal structure is more important than the external quality. 3D printing uses 15-20% packing density, but shielding should be set to 100% packing density. This is because, as the packing density increases, the material of the filament used reacts with the intensity of radiation and radiation attenuation to shield the radiation.Nozzle size and bed height were chosen as key parameters. The nozzle sizes were changed to 0.4, 0.6, and 0.8 mm, and the layer height was changed to 0.1, 0.2, 0.3, and 0.4 mm, respectively. Additionally, the filament thickness varied between 1.75mm and 2.85mm. The main results were that the shielding performance was irregular with the change in nozzle size, and the shielding performance increased with decreasing layer height and thicker filament thickness. Printing time also decreased as nozzle size and layer height increased and filament thickness increased. In this study, the shielding performance was shown to be affected by the parameters, and it was confirmed that the correct use of the parameters in shielding production improves the shielding performance. This can provide basic data for 3D printed shielding manufacturing.

Keywords
3D printing, Fused Filament Fabrication, Radiation shielding, Copper blended filament, nozzle size, layer height

Introduction

3D printing technology can produce products of the desired shape of digital data onto various materials. 3D printing uses Additive manufacturing (AM) to build products layer by layer, as opposed to Subtractive manufacturing (SM).[1] Among the AM, the FFF (Fused Filament Fabrication) is a method in which filament, which are 3D printer materials, are melted and jetted from a nozzle to form one layer at a time.[2]Advantages of FFF include the availability of various

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materials and competitive prices.[2,3,4]This is the main reason why it is most commercialized in the additive manufacturing industry today.[2] FFF process uses thermoplastic filament, the range of filament materials is rapidly expanding.[5] Low-density plastic filament such as PLA (poly lactic acid) and ABS (acrylonitrile butadiene styrene) are mostly used, and high-density blended filament of metals such as aluminum, copper, tungsten, and bismuth are also widely used.[6-13] The reason is that, first, the pure metal has high melting point and is difficult to process, but after mixing with PLA, ABS, etc., the melting point is relatively low and processing are easier.Second, in the case of shielding materials, the higher the atomic density, the better the shielding ability, but in the case of blended filament, the atomic density is high.[7] Third, the price of pure metal 3D printer and pure metal filament is high, and the price competitiveness of products is reduced.For this reason, the metal-blended filament is used in various industries.To improve the perfection of the metal-blended filament printout, it is necessary to understand the principle of 3D printers and to be excellent in the combination of parameter setting of intrinsic factors and additional factors.Intrinsic factors include the atomic number and density of the material, and additional factors include nozzle size, layer height, internal pattern, and infill density.[3,14] The parameter study of product characteristics is an important subject for quality improvement.[2,15] Appropriately adjusting the additional factors between the parameter, the quality of the printout can be improved.[14] Among them, in the case of a shielding produced by a 3D printer, the internal structure is more important than the external quality.In 3D printing, use 15-20% infill density, but the shielding must be set to 100% infill density.This is because, as the infill density increases, the material of the filament used reacts with the radiation, the intensity of the radiation attenuation, and the radiation is shielded.However, when printing is performed after setting the infill density to 100%, the printing speed is doubled, and if the filament is not extruded 100% due to mechanical error, an air-gap occurs and the shielding efficiency is reduced. For this reason, parameter control is essential. The important parameter related to infill density is nozzle size and layer height.The layer height is determined by the nozzle size, and as the nozzle size increases, the layer height increases proportionally to the nozzle size.Therefore, if the layer height is increased by increasing the nozzle size, a large amount is printing at one time, so the printing time can be reduced, and the internal quality, which is important for the shielding, can be improved.Although the shielding rate can be improved by researching setting this parameter, the research on parameter setting is not enough.[16]In addition, compared with filament such as PLA and ABS, metal-blended filament is difficult to use due to the easy accumulation of impurities in the nozzle, so there are few studies on shielding made of metal-blended filament.However, metal-blended filament is emerging as a replacement for lead from the harmful effects of lead, which is commonly used in clinical practice.In this study, a shielding was printed with FFF using a copper-blended filament, which confirmed its potential as a shielding material, and through experiments, the effect of nozzle size and layer height on shielding ability is to be analyzed.

Materials and Method

Shielding was fabricated by varying the nozzle size and layer height using FFF 3D printer.The experiment was performed in the same order as in Figure 1.

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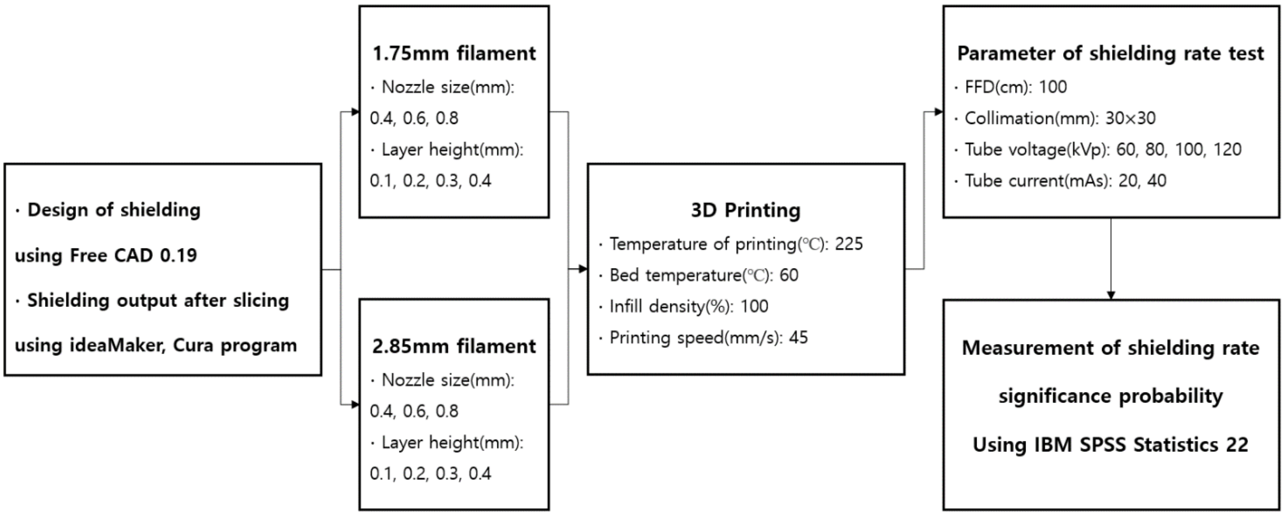

Fig. 1. Flow chart of experiments on shielding performance due to changing parameter settings of 3D printer.

2.1. Shielding design

Using the Open Source Free CAD 0.19 program, a 60 × 60 × 4 mm shielding was 3D designed, as shown in Figure 2, and saved in STL (StereolithoGraphy) format for 3D printing.

2.2. Parameter setting by slicing program, shielding printing

Designed 3D shielding STL file by slicing program ideaMaker (4.0.1, USA) and Cura (4.9.0, Ultimaker, Netherlands) to generate G-code nozzle size 0.4, 0.6, 0.8 mm, layer height was set to 0.1, 0.2, 0.3 and 0.4 mm.Copper blended filament used two thicknesses of 1.75 and 2.85 mm, 1.75 mm in ideaMaker and 2.85 mm in Cura. After setting the temperature of printing, bed temperature, infill density, printing speed, etc. in Table 1., slicing was performed.Then, the G-code generated for output is transmitted to the device using the network, and Fig. 2 Shielding was printing as shown.

Table 1. Setting value of 3D printer.

Radiation shielding	
Nozzle size (mm)	0.4, 0.6, 0.8
Layer height (mm)	0.1, 0.2, 0.3, 0.4
Temperature of printing (℃)	225
Bed temperature (℃)	60
Infill density (%)	100
Printing speed (mm/s)	45

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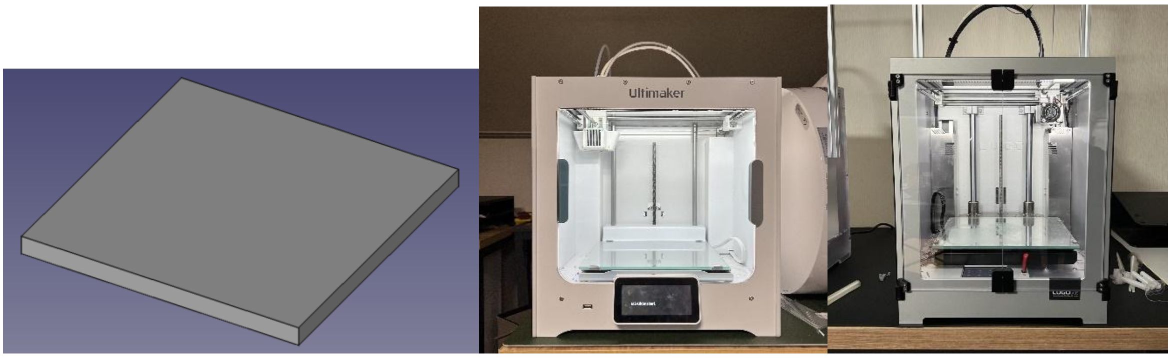

(a) (b) (c)

Fig. 2. Used 3D printer and 3D modeling (a) 3D modeling of shielding (b), (c) 3D printer

2.3. Shielding printing time measurement

Depending on the filament thickness, we used ideaMaker for 1.75 mm and Cura for 2.85 mm, and proceeded with slicing after setting the parameter.In addition, it was attempted to confirm the change in the printing time of the shielding according to the additional factors such as nozzle size, layer height, and filament thickness.

2.4. Dose testing with manufactured shielding

In order to check the effect of nozzle size and layer height as additional factors on the shielding performance of shielding fabricated using copper blended filament and FFF 3D printer, experiment was conducted as follows.First, the distance between the X-ray tube and the shielding was set to 1000 mm for dosimeter, and the distance from the shielding to the dosimeter (Magic Max Universal, Germany) was 50 mm to prevent scatter ray.Collimation is set to 30 x 30 mm.Second, parameter, the tube voltage was changed to 60, 80, 100, 120 kVp, and the tube current was changed to 20, 40 mAs, and the experiment was carried out.For the experimental equipment, diagnostic X-ray imaging equipment (DR System, GX-650H, Dong Kang Korea) and dosimeter were used.First, without putting anything on the dosimeter, exposure X-ray three times for each tube voltage and tube current.(Fig. 3)After that, shielding with different nozzle size and layer height is placed on the dosimeter in turn, and X-ray exposure three times, the average value of the measured radiation dose was calculated.The detailed parameter is shown in Table 2.

Table 2. Parameter for dose measurement.

Parameter	Tube voltage [kVp]	Tube current [mAs]	Collimation [mm]
Value	60, 80, 100, 120	20, 40	30 x 30

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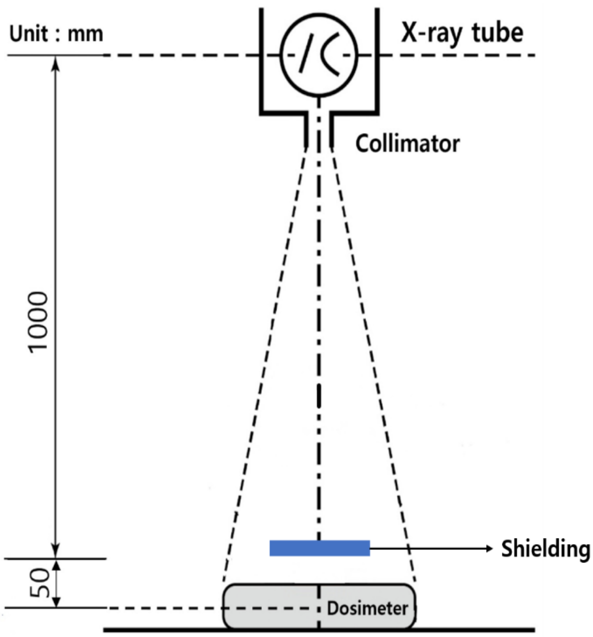

(a)

(b)

Fig. 3. Shielding rate test arrangement (a) Experimental drawing (b) Experiments conducted with the manufactured shielding.

Result

3.1. Printout production results

Two types of filament thicknesses were used: 1.75 mm and 2.85 mm, and the shape of the printed shielding was the same.The shielding for this study is fabricated in the Fig. 4.

Fig. 4.Radiation shielding. Shielding made by varying nozzle size and layer height as each filament is printed.

3.2. 3D printer printing time varying as a function of the additional factor of the shielding made of 1.75 mm filament

Fig. 5 (a) Shows the printing time variation of shielding made of 1.75 mm filament.With a nozzle size of 0.4 mm, depending on the layer height, 0.1 mm took 199 minutes, 0.2 mm took 107 minutes,

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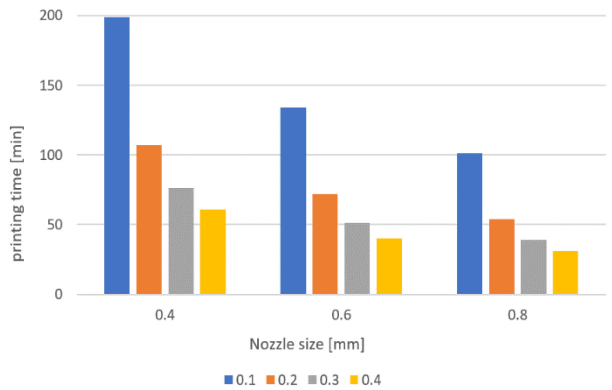
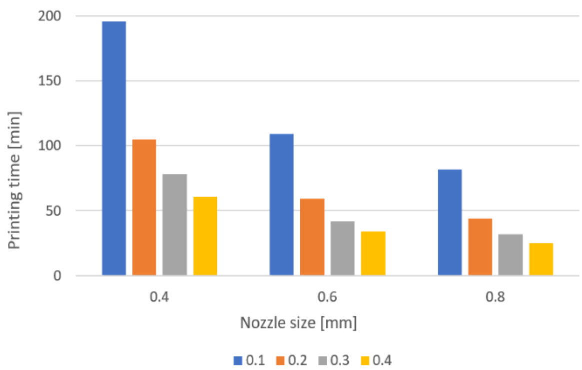
0.3 mm took 76 minutes, and 0.4 mm took 61 minutes.With a nozzle size of 0.6 mm, in terms of layer height, 0.1 mm took 134 minutes, 0.2 mm took 72 minutes, 0.3 mm took 51 minutes, and 0.4 mm took 40 minutes.With a nozzle size of 0.8 mm, in terms of layer height, 0.1 mm took 101 minutes, 0.2 mm took 54 minutes, 0.3 mm took 39 minutes, and 0.4 mm took 31 minutes. (Table 3.)

3.3. 3D printer printing time varying as a function of the additional factor of the shielding made of 2.85 mm filament 2.85 mm

Fig. 5 (b) Shows the printing time variation of a shield made of 2.85 mm filament.With a nozzle size of 0.4 mm, depending on the layer height, 0.1 mm took 196 minutes, 0.2 mm took 105 minutes, 0.3 mm took 72 minutes, and 0.4 mm took 61 minutes.With a nozzle size of 0.6 mm, in terms of layer height, 0.1 mm took 109 minutes, 0.2 mm took 59 minutes, 0.3 mm took 42 minutes, and 0.4 mm took 34 minutes.With a nozzle size of 0.8 mm, in terms of layer height, 0.1 mm took 82 minutes, 0.2 mm took 44 minutes, 0.3 mm took 32 minutes, and 0.4 mm took 25 minutes. (Table 3.)



(a)



(b)

Fig. 5. Printing time of shielding made with each filament. (a) Shielding with 1.75 mm filament takes at least 31 minutes to a maximum of 199 minutes depending on the size of the nozzle. (b) Shielding with 2.85 mm filament takes at least 25 minutes to a maximum of 196 minutes depending on the size of the nozzle.

3.4. Shielding performance experiment results of 1.75 mm filament shielding

Table 3. Shows the shielding performance of each shielding made of 1.75 mm filament for each parameter. It is the best shielding performance in a shielding made of 1.75 mm filament, 0.1 mm layer height, 0.4 mm nozzle size, 0.99 mR at 60 kVp 20 mAs, 96.68 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 1.04 mR at 60 kVp 20 mAs, 100.3 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 1.02 mR at 60 kVp 20 mAs and 99.57 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.4 mm, 0.8 mm, and 0.6 mm is the best in this order. It is the best shielding performance in 0.2 mm layer height, 0.4 mm nozzle size, 1.11 mR at 60 kVp 20 mAs, 101.27 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 1.04 mR at 60 kVp 20 mAs, 99.86 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 1.06 mR at 60 kVp 20 mAs and 101.2 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.4 mm is better than 0.8 mm at low tube voltages of 60 and 80 kVp and did not appear regularly at high tube voltages of 100 and 120 kVp. It is the best

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shielding performance in 0.3 mm layer height, 0.4 mm nozzle size, 1.08 mR at 60 kVp 20 mAs, 100.6 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 1.07 mR at 60 kVp 20 mAs, 101.17 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 1.06 mR at 60 kVp 20 mAs and 100.07 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.8 mm is the best, with 0.4 mm being better than 0.6 mm at 60 kVp and 0.6 mm being better than 0.4 mm at 80, 100 and 120 kVp. It is the best shielding performance in 0.4 mm layer height, 0.4 mm nozzle size, 1.1 mR at 60 kVp 20 mAs, 101.5 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 1.09 mR at 60 kVp 20 mAs, 101.83 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 1.07 mR at 60 kVp 20 mAs and 100.63 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.8 mm is the best and, unlike the low tube voltage, 0.6 mm is better than 0.4 mm at high tube voltages of 100 and 120 kVp.

3.5. Shielding performance experiment results of 2.85 mm filament shielding

Table 3. Shows the shielding performance of each shielding made of 2.85 mm filament for each parameter. It is the best shielding performance in a shielding made of 2.85 mm filament, 0.1 mm layer height, 0.4 mm nozzle size, 0.65 mR at 60 kVp 20 mAs, 85.83 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 0.75 mR at 60 kVp 20 mAs, 86.99 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 0.73 mR at 60 kVp 20 mAs and 85.24 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.4 mm, 0.8 mm, and 0.6 mm is the best in this order. It is the best shielding performance in 0.2 mm layer height, 0.4 mm nozzle size, 0.71 mR at 60 kVp 20 mAs, 86.27 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 0.82 mR at 60 kVp 20 mAs, 91.13 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 0.69 mR at 60 kVp 20 mAs and 85.9 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.8 mm, 0.4 mm, and 0.6 mm is the best in this order. It is the best shielding performance in 0.3 mm layer height, 0.4 mm nozzle size, 0.92 mR at 60 kVp 20 mAs, 94.74 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 0.85 mR at 60 kVp 20 mAs, 92.7 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 0.77 mR at 60 kVp 20 mAs and 86.94 mR at 120 kVp 40 mAs. As a result, the nozzle size of 0.8 mm, 0.6 mm, and 0.4 mm is the best in this order. It is the best shielding performance in 0.4 mm layer height, 0.4 mm nozzle size, 0.97 mR at 60 kVp 20 mAs, 96.95 mR at 120 kVp 40 mAs, 0.6 mm nozzle size, 0.97 mR at 60 kVp 20 mAs, 97.4 mR at 120 kVp 40 mAs and 0.8 mm nozzle size, 0.82 mR at 60 kVp 20 mAs and 91.58 mR at 120 kVp 40 mAs. As a result, 0.8 mm nozzle size is the best, 0.4 mm is better than 0.6 mm at low tube voltages of 60 and 80 kVp, and 0.6 mm is better than 0.4 mm at high tube voltages of 100 and 120 kVp.

Table 3. Dose average, printing time of the shielding by filament thickness and parameters.

Average (Standard deviation)									
Nozzle size [mm]	Layer height [mm]	0.1		0.2		0.3		0.4	
	Filament thickness [mm]	1.75	2.85	1.75	2.85	1.75	2.85	1.75	2.85

0.4	60 kVp	20 mAs	0.99(0.003)	0.65(0)	1.10(0.006)	0.71(0.002)	1.08(0.002)	0.92(0.001)	1.10(0.006)	0.97(0.020)
		40 mAs	1.95(0.004)	1.28(0.003)	2.17(0.005)	1.40(0.002)	2.13(0.006)	1.81(0.001)	2.16(0.003)	1.93(0)
	80 kVp	20 mAs	7.09(0.011)	5.65(0.018)	7.62(0.030)	6.00(0.009)	7.56(0.010)	6.96(0.010)	7.65(0.008)	7.28(0.019)
		40 mAs	14.32(0.015)	11.40(0.006)	15.36(0.031)	12.13(0.015)	15.22(0.015)	14.15(0.01)	15.42(0.006)	14.46(0.211)
	100 kVp	20 mAs	23.16(0.104)	19.23(0.006)	24.43(0.021)	20.15(0.025)	23.21(0.045)	22.57(0.057)	24.54(0.058)	23.22(0.034)
		40 mAs	46.07(0.095)	38.28(0.030)	48.63(0.051)	40.07(0.031)	48.28(0.015)	44.90(0.01)	48.84(0.017)	46.17(0.015)
	120 kVp	20 mAs	49.43(0.124)	42.38(0.104)	51.65(0.055)	44.07(0.12)	51.33(0.172)	48.45(0.071)	51.72(0.026)	49.55(0.025)
		40 mAs	96.68(0.095)	82.83(0.110)	101.27(0.115)	86.27(0.076)	100.6(0)	94.74(0.052)	101.5(0)	96.95(0.050)
	Printing time [min]		199	196	107	105	76	72	61	61
0.6	60 kVp	20 mAs	1.04(0)	0.75(0.002)	1.038(0.007)	0.82(0.001)	1.07(0)	0.85(0.003)	1.09(0.002)	0.97(0.003)
		40 mAs	2.04(0.003)	1.46(0.004)	2.07(0.009)	1.42(0.003)	2.11(0.004)	1.67(0.002)	2.15(0.003)	1.90(0.003)
	80 kVp	20 mAs	7.46(0.004)	6.14(0.021)	7.45(0.018)	6.51(0.100)	7.61(0.010)	6.67(0.105)	7.69(0.009)	7.12(0.013)
		40 mAs	14.99(0.021)	12.41(0.026)	15.02(0.006)	13.17(0.247)	15.31(0.025)	13.31(0.194)	15.44(0.006)	14.34(0.006)
	100	20 m	24.14(0.038)	20.56(0.023)	24.17(0.057)	21.52(0.015)	24.47(0.035)	21.96(0.025)	24.64(0.017)	23.30(0.051)

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	k	As								
	Vp	40 mAs	47.94(0.025)	40.82(0.04)	47.91(0.01)	42.78(0.044)	48.65(0.038)	43.59(0.012)	48.95(0.036)	46.34(0.040)
	120 kVp	20 mAs	51.37(0.067)	44.79(0.023)	51.22(0.071)	46.60(0.049)	51.82(0.04)	47.47(0.061)	52.10(0.053)	49.84(0.046)
		40 mAs	100.3(0)	86.99(1.239)	99.86(0.044)	91.13(0.01)	101.17(0.115)	92.70(0.042)	101.83(0.058)	97.40(0.072)
	Printing time [min]		134	109	72	59	51	42	40	34
0.8	60 kVp	20 mAs	1.02(0.003)	0.73(0.004)	1.06(0.004)	0.69(0.004)	1.06(0.002)	0.77(0.004)	1.07(0.004)	0.82(0.004)
		40 mAs	2.00(0.005)	1.42(0.002)	2.09(0.004)	1.36(0.003)	2.07(0)	1.52(0.005)	2.11(0.007)	1.62(0.004)
	80 kVp	20 mAs	7.41(0.023)	6.10(0.020)	7.60(0.017)	5.95(0.020)	7.48(0.010)	6.35(0.006)	7.57(0.027)	6.57(0.090)
		40 mAs	14.87(0.006)	12.30(0.015)	15.29(0.01)	12.00(0.006)	15.04(0.015)	12.78(0.006)	15.21(0.015)	13.21(0.179)
	100 kVp	20 mAs	23.97(0.031)	20.45(0.035)	24.45(0.040)	20.06(0.02)	24.21(0.044)	20.99(0.01)	24.30(0.012)	21.69(0.025)
		40 mAs	47.64(0.064)	40.56(0.038)	48.56(0.025)	39.82(0.03)	48.07(0.025)	41.7(0.01)	48.35(0.01)	43.06(0.01)
	120 kVp	20 mAs	50.90(0.059)	44.64(0.029)	51.78(0.025)	43.97(0.042)	51.25(0.023)	45.73(0.053)	51.46(0.067)	46.88(0.031)
		40 mAs	99.57(0.046)	85.24(0.040)	101.2(0.1)	85.90(0.012)	100.07(0.058)	86.94(4.068)	100.63(0.058)	91.58(0.035)
	Printing time [min]		101	82	54	44	39	32	31	25

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DISCUSSION

The use of shielding for radiation protection is increasing from printing materials using 3D printing technology in medicine. In the process of making such shielding, 3D printing technology is needed to reduce production costs and time.[17,18] There are many studies trying to use 3D printer to fabricate shielding using metal-blended filament through the FFF (Fused Filament Fabrication). According to the study by Yin. et al., conducted experiments on tensile strength and neutron shielding properties by varying nozzle speed and nozzle temperature using Boron carbide/ PEEK (poly-ether-ether-ketone) as a blended filament.[19] According to another study by Yin. et al., PEEK/tungsten composites were fabricated by varying the nozzle temperature of PEEK/tungsten-blended filament, and the tensile strength, flexural properties, and gamma-ray shielding performance were also evaluated.[20]Like Yin.et al.'s research, there are many studies that have experimented with creating shielding by varying nozzle speed and temperature of printing etc. as parameter for 3D printer. However, we know that there are no studies looking at differences in shielding performance according to nozzle size and layer height like this study. Therefore, studies on shielding performance improvement considering the parameter of 3D printer are still insufficient. In this study, we used filaments of two thicknesses, 1.75 mm and 2.85 mm, the nozzle size set at 0.4, 0.6, 0.8 mm, and the layer height set at 0.1, 0.2, 0.3, 0.4 mm. In addition, lead, which is most used for clinically, is harmful to humans and the environment, so it is being regulated by OECD member countries to reduce its use.[21] Therefore, a lot of research is going on to find materials to replace lead, such as Bi-Sn-Zn alloys and diaspore-fly ash concrete.[7,22] Copper blended filament was used, which in previous studies confirmed the possibility of radiation shielding. The experiment was conducted with X-rays, which are most commonly used in clinical practice. Through experiment, the following results can be obtained. Printing time decreases by a maximum of about 2.44 times with increasing nozzle size, about 4.04 times with increasing layer height, and about 1.24 times with increasing filament thickness. The dose differenced according to filament thickness was up to 15.3 mR, the thicker the filament, the better the shielding performance. Depending on the layer height, the dose difference was as high as maximum 14.13 mR, and the lower the layer height, the higher the performance. The dose differenced according to nozzle size was as high as maximum 7.81 mR. A nozzle size of 0.4 mm is the best at 0.1 mm layer height, while at 0.2 mm layer height the dose variation was irregular, making it impossible to find the best nozzle size. A nozzle size of 0.8 mm showed the best performance at layer height of 0.3 and 0.4 mm. However, since metal-blended filaments can clog or wear nozzles due to impurities, filament manufacturers also recommend using a nozzle size of 0.6 mm or larger when using metal-blended filaments. Therefore, considering the shielding performance, printing time and the recommendations of the filament manufacturer, the nozzle size of 0.8 mm is better than 0.4 mm in both the shielding performance and the mechanical aspects of the 3D printer. These results are expected to be based on ideal additional factor the parameter when manufacturing sheilding using the 3D printer. In conducting this experiment, there is a limitation that shielding made of copper blended filament are more expensive than lead shielding and plastic filaments, but less expensive than shielding made of pure metal. However, First, the study used copper-blended filament, which are difficult to print compared to PLA and ABS filament. Second, metal-blended filament shielding is made that is less harmful than lead. In conclusion, the performance of the shielding increases the additional factor of 3D printing technology, as the nozzle size, layer height and filament thickness increase, the production time is reduced and the shielding efficiency is more higher.

CONCLUSION

In this study, parameter, nozzle size and layer height, were used to confirm the shielding performance according to the change in the additional factor of the shielding of copper-blended filament. As a result of the experiment, the shielding performance is decreased by a maximum of 15.3 mR according to the change of the parameter. In addition, the printing time decreased by a maximum of 7.96 times depending on the parameter. These points, this study is considered to be able to provide basic data onto the production of 3D printed shielding.

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