

# A novel radiation-shielding undergarment using tungsten functional paper for patients with permanent prostate brachytherapy

Masahiro Inada<sup>1</sup>, Hajime Monzen<sup>2,\*</sup>, Kenji Matsumoto<sup>2</sup>, Mikoto Tamura<sup>2</sup>, Takafumi Minami<sup>3</sup>, Kiyoshi Nakamatsu<sup>1</sup> and Yasumasa Nishimura<sup>1</sup>

<sup>1</sup>Department of Radiation Oncology, Kindai University Faculty of Medicine, 377-2, Ohno-Higashi, Osaka-Sayama, Osaka, Japan

<sup>2</sup>Department of Medical Physics, Kindai University Faculty of Medicine, 377-2, Ohno-Higashi, Osaka-Sayama, Osaka, Japan

<sup>3</sup>Department of Urology, Kindai University Faculty of Medicine, 377-2, Ohno-Higashi, Osaka-Sayama, Osaka, Japan

\*Corresponding author. Department of Medical Physics, Kindai University Faculty of Medicine, 377-2, Ohno-Higashi, Osaka-Sayama, Osaka, Japan.

Tel: +81-72-366-0221; Email: hmon@med.kindai.ac.jp

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## ABSTRACT

Tungsten functional paper (TFP) is a paper-based radiation-shielding material, which is lead-free and easy to cut. We developed a radiation protection undergarment using TFP for prostate cancer patients treated with permanent <sup>125</sup>I seed implantation (PSI). The aim of this study was to evaluate the shielding ability of the undergarment with respect to household contacts and members of the public. Between October 2016 and April 2017, a total of 10 prostate cancer patients treated with PSI were enrolled in this prospective study. The external radiation exposure from each patient 1 day after PSI was measured with and without the undergarment. Measurements were performed using a survey meter at 100 cm from the surface of the patient's body. The exposure rates were measured from five directions: anterior, anteriorly oblique, lateral, posteriorly oblique, and posterior. The measured radiation exposure rates without the undergarment, expressed as mean ± standard deviation, from the anterior, anteriorly oblique, lateral, posteriorly oblique, and posterior directions were 1.28 ± 0.43 µSv/h, 0.70 ± 0.34 µSv/h, 0.21 ± 0.062 µSv/h, 0.65 ± 0.33 µSv/h and 1.24 ± 0.41 µSv/h, respectively. The undergarment was found to have (mean ± standard deviation) shielding abilities of 88.7 ± 5.8%, 44.0 ± 42.1%, 50.6 ± 15.9%, 72.9 ± 27.0% and 90.4 ± 10.7% from the anterior, anteriorly oblique, lateral, posteriorly oblique, and posterior directions, respectively. In conclusion, this shielding undergarment is a useful device that has the potential to reduce radiation exposure for the general public and the patient's family.

**Keywords:** prostate brachytherapy; radiation-shielding undergarment; seed; prostate cancer

## INTRODUCTION

Permanent seed implant brachytherapy (PSI) achieves a high relapse-free survival rate, comparable with that of surgery, for clinically localized prostate cancer [1, 2]. However, there remains a concern about the incidental radiation exposure to patients' family members and the general public [3–7]. Because of a general fear of radiation exposure among the public, some patients refuse PSI, and patient anxiety cannot always be alleviated by appropriate education, although some studies have shown that the radiation exposure to family members and the general public is very low [3–6]. Additionally, according to the 'as low

as is reasonably achievable' principle [8], exposure to ionizing radiation should always be minimized as much as possible. Patients sometimes purchase radiation-shielding undergarments [9]. Currently, only lead-lined underwear is available. The lead-based undergarments pose several issues, including the cost and the toxicity to the human body and the environment [10]. The European Union directive Restriction of the Use of Certain Hazardous Substances (in electrical and electronic equipment), prohibited the use of lead in electrical appliances after 1 July 2006. There is therefore a strong demand for lead-free product development in health-care and industrial applications [11].

**Table 1. Patient characteristics and treatment**

Patient no.	Age (years)	Weight (kg)	BMI (kg/m <sup>2</sup> )	Prescribed BT dose (Gy)	Implanted seed number	Total implant activity (MBq)	Prostate volume (ml)	EBRT Dose (Gy)
1	57	68.2	25.8	144	75	751.5	30.2	0
2	68	74.0	24.2	100	90	1112.2	73.0	40
3	67	68.6	23.1	144	80	801.6	31.2	0
4	65	77.9	28.0	144	85	1050.4	44.4	0
5	72	66.9	24.7	100	68	681.3	39.8	40
6	79	62.2	22.3	110	52	539.6	17.8	45
7	70	60.9	20.9	144	85	851.7	31.9	0
8	68	54.6	23.9	144	60	622.6	17.4	0
9	61	62.4	21.5	100	63	653.7	28.8	40
10	74	57.8	22.8	144	72	747.1	18.7	0

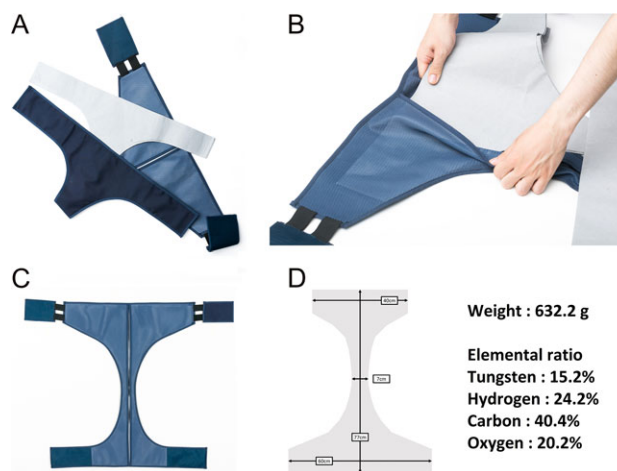
BMI = body mass index, BT = brachytherapy, EBRT = external beam radiation therapy.

Tungsten functional paper (TFP) is a material with radiation-shielding properties. It is easy to cut, fold and stick onto other materials. The TFP is lead-free, so is less harmful to the body than lead-containing materials and can be applied to a patient's body surface [11, 12]. It is also recyclable [10]. We developed a radiation-shielding device using TFP as a prototype. The aim of this study was to evaluate the shielding potential of a TFP undergarment after PSI.

## MATERIALS AND METHODS

This prospective trial was approved by the Institutional Review Board of our hospital in September 2016 (2016–123). All patients signed informed consent before entering the study. Between October 2016 and April 2017, ten patients with localized prostate cancer who were scheduled for PSI [with or without supplemental external beam radiotherapy (sEBRT) following PSI] were enrolled. Patient characteristics and treatment plans are summarized in Table 1. All patients underwent a transrectal ultrasound examination 2–4 weeks before implantation to determine the number of seeds needed. Seed implantations were performed using a dynamic dose calculation technique [13].

The weighted mean photon energy of <sup>125</sup>I is 28 KeV. The <sup>125</sup>I seeds used at our hospital are Oncoseed® (GE Healthcare, Arlington Heights IL, USA), Brachysource, (CR Bard, Covington GA, USA) or TheraAgX100® (Theragenic Corporation, Buford, GA, USA). The TFP (Toppan Printing Corporation, Tokyo, Japan) is 0.3 mm thick and can be cut with scissors and folded into different shapes or forms. The relative specific gravities of the tungsten powders included in a single sheet of the TFP are 80.5% for tungsten. The elemental ratios in the TFP (mol%) are H: 24.2%, C: 40.4%, O: 20.2% and W: 15.2% [10]. Three sheets of the TFP were designed and cut and covered by a cotton and polyester fabric (Fig. 1). The undergarment required 1994 cm<sup>2</sup> of the TFP per sheet, and the total weight of the TFP undergarment was 632.2 g (Fig. 1). The undergarment was put over the patient's pants (Fig. 2).



**Fig. 1. (A–B) The structure of tungsten functional paper (TFP) and its container. (C) The undergarment. (D) Geometry of TFP. The undergarment required 1994 cm<sup>2</sup> of TFP.**

Radiation exposure measurements were obtained using a TCS-173C NaI(Tl) scintillation survey meter (Hitachi Healthcare, Tokyo, Japan). The survey meter was calibrated with a <sup>129</sup>I source. The measurements were performed 24 h after seed implantation with and without the undergarment. The measurements were performed in the standing position from five directions as follows: anterior (0°), anteriorly oblique (45°), lateral (90°), posteriorly oblique (135°) and posterior (180°) (Fig. 3). The measurements with the survey meter were made 100 cm from the surface of the patient. Each of the distances and angles were measured using a ruler and angle gauge. The mean of five measurements was used. The shielding percentages were obtained from the exposure rate from each patient with (D[g]) and without (D[n]) the undergarment as follows:

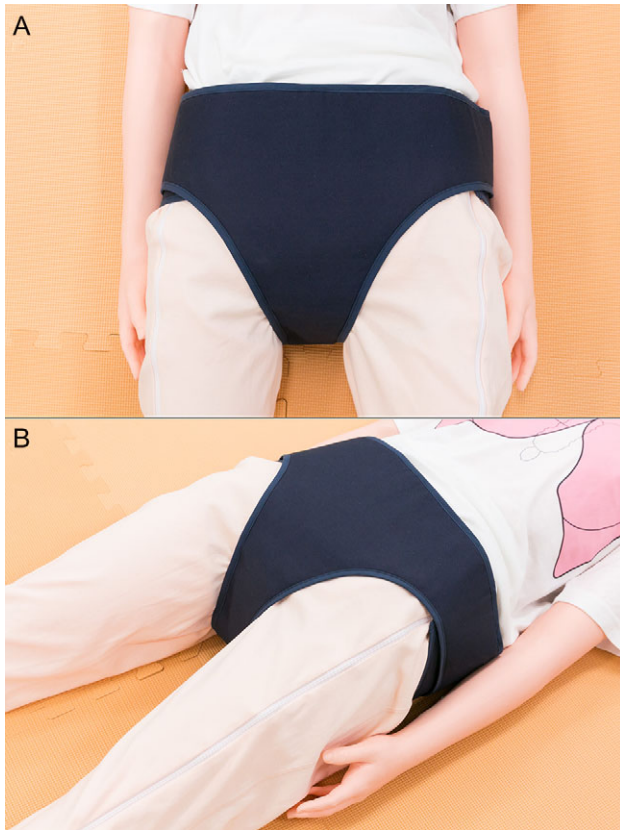


Fig. 2. The undergarment was put onto the patient's pants. (A) Front view. (B) Oblique view.

$$\text{Shielding rate} = \frac{D(n) - D(g)}{D(n)} \times 100 \quad (1)$$

To compare the radiation exposure rate for each patient when wearing the TFP radiation protection undergarment compared with that when not wearing it, one-way analysis of variance was performed. Probability ( $P$ ) values of  $<0.05$  were considered significant.

## RESULTS

Eight out of the ten patients had complete measurements from the five directions. The remaining two patients did not undergo the radiation measurement in the posteriorly oblique and posterior directions because of misunderstanding of the protocol. The measured radiation exposure rates (mean  $\pm$  standard deviation) without the undergarment from anterior, anteriorly oblique, lateral, posteriorly oblique and posterior directions were  $1.28 \pm 0.43 \mu\text{Sv/h}$ ,  $0.70 \pm 0.34 \mu\text{Sv/h}$ ,  $0.21 \pm 0.062 \mu\text{Sv/h}$ ,  $0.65 \pm 0.33 \mu\text{Sv/h}$  and  $1.24 \pm 0.41 \mu\text{Sv/h}$ , respectively. Wearing the undergarment, the measured radiation exposure rates (mean  $\pm$  standard deviation) from each direction were  $0.14 \pm 0.082 \mu\text{Sv/h}$ ,  $0.38 \pm 0.37 \mu\text{Sv/h}$ ,  $0.098 \pm 0.033 \mu\text{Sv/h}$ ,  $0.15 \pm 0.14 \mu\text{Sv/h}$  and  $0.12 \pm 0.15 \mu\text{Sv/h}$ , respectively. The radiation-shielding proportions (mean  $\pm$  standard deviation) from the anterior, anteriorly oblique, lateral, posteriorly oblique and posterior directions were  $88.7 \pm 5.8\%$ ,  $44.0 \pm 42.1\%$ ,  $50.6 \pm 15.9\%$ ,  $72.9 \pm 27.0\%$  and

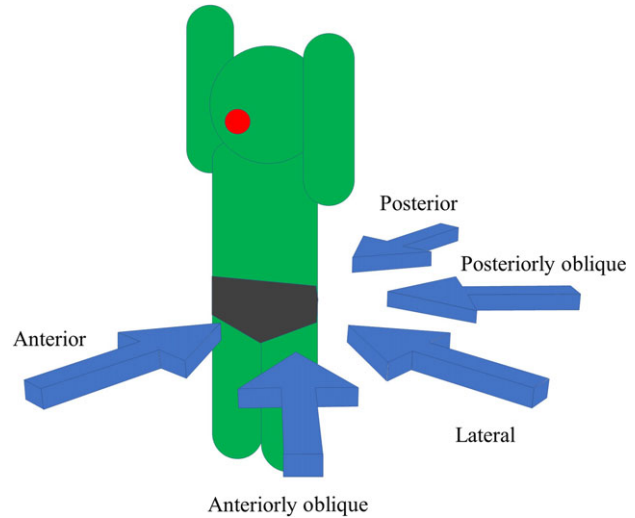


Fig. 3. The radiation exposure rates were measured from five directions.

$90.4 \pm 10.7\%$ , respectively (Fig. 4). For all directions, there was significant reduction in the radiation exposure rate when wearing the TFP radiation protection undergarment (anterior:  $P < 0.001$ , anteriorly oblique:  $P = 0.018$ , lateral:  $P < 0.001$ , posteriorly oblique:  $P = 0.0089$  and posterior:  $P < 0.001$ ).

## DISCUSSION

We measured the direct radiation exposure rate after  $^{125}\text{I}$  PSI with and without the undergarment, and demonstrated excellent shielding ability of the undergarment. The undergarment achieved  $\sim 90\%$  exposure reduction from the anterior and posterior directions. The directions with the largest amount of radiation exposure without shielding were the anterior and posterior directions, which had approximately six times the amount of radiation exposure as that in the lateral direction. Wearing the undergarment, the radiation exposure from the anterior and posterior directions decreased to  $\sim 10\%$  as the same level as the lateral direction. This shielding, thus, can efficiently reduce the radiation exposure to household contacts and the general public. Based on the present results, a new undergarment is being planned with reduced weight and cost, and improved comfort, without impairing the shielding ability. Hanada *et al.* [7] reported that weight and BMI correlated with the radiation dose rate measured from patients after PSI, suggesting that body characteristics are an important factor to be taken into account with respect to radiation dose rate. Protection wear would seem to be more important for thin patients, commonly represented in Japanese elderly man. However, in this study, the shielding ability of the TFP undergarment did not correlate to  $\sim$ BMI or weight (data have not been shown and correlations were tested using Pearson's product-moment correlation coefficient).

Lead-lined undergarments are commercially available to patients with permanent radioactive implants, to reduce radiation exposure for the public and for family [7, 14]. However, the lead-lined undergarments contain materials toxic to the human body and to the

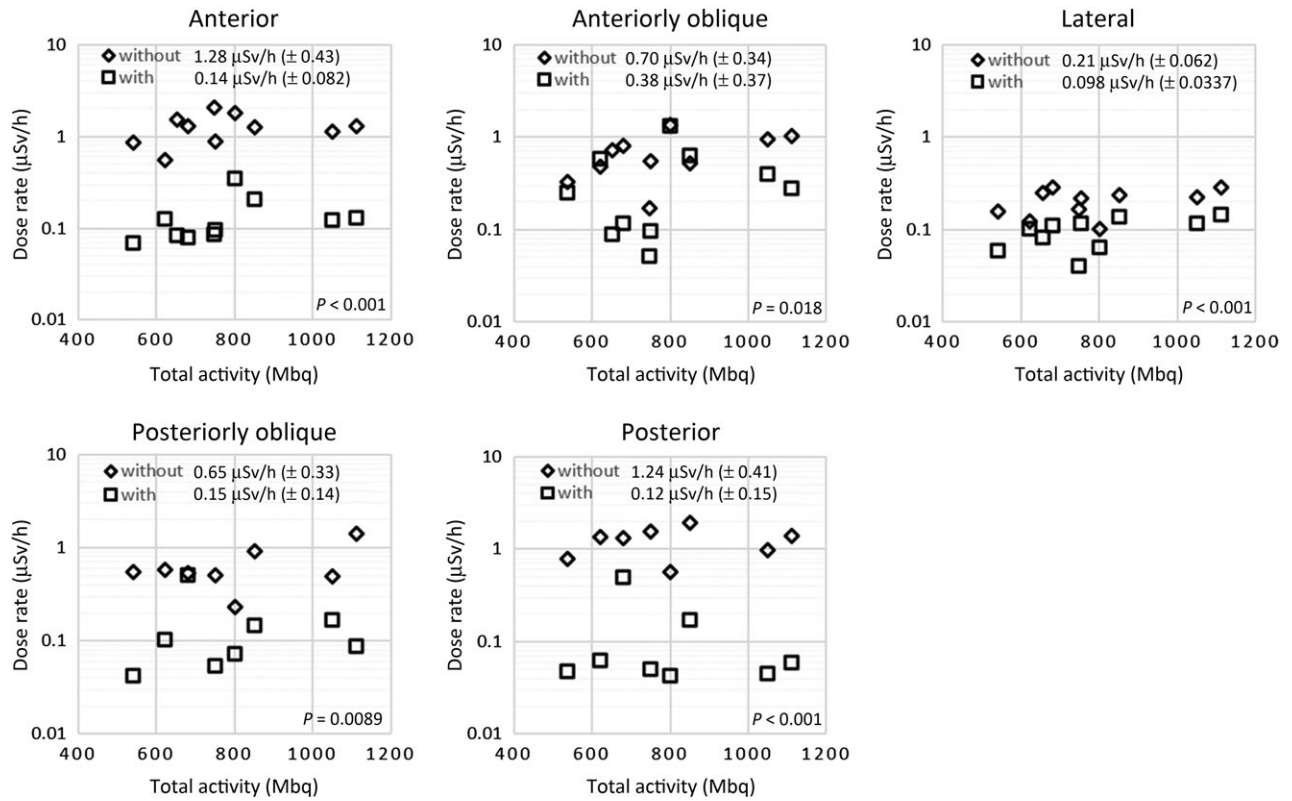


Fig. 4. Scatter plots that described the relationship between the radiation dose rate and the total activity for each measurement. Values were given as mean ( $\pm$ standard deviation).

environment. The TFP undergarment can be an alternative option to the lead-lined undergarment for patients treated with PSI. In addition, it is advantageous that the TFP can be recycled [10, 15]. Hanada *et al.* reported that a lead-lined undergarment can attenuate the exposure rate in the anterior direction by  $\sim 95.8\%$  [7]. In the present study, we found that the exposure reduction of three sheets of TFP was similar to that of a commercially available lead-lined undergarment in the anterior direction. It would be easy to improve the shielding ability of the undergarment further by use of more sheets of TFP. However, each additional TFP sheet costs  $\sim$ US\$100. Three sheets of TFP seems to strike a good balance between cost and shielding ability. The advantages of the TFP undergarment compared with the lead-lined undergarment are its lower toxicity and its recycling ability [10–12, 15]. Although previous data have shown that the radiation exposure to the general public is low and that patients need not be concerned about the radiation exposure risk [3–6], there are still patients and their families who have strong fears about radiation exposure. For the patients and their families with such concerns, the undergarment may be useful.

According to the guidelines on PSI from the Japanese government, patients treated with PSI can be released from the treatment room if the implanted activity is  $\leq 1300$  MBq or if the exposure equivalent 1 m from the patient's skin surface is  $\leq 1.8$   $\mu$ Sv/h. As it is known that biochemical control after PSI depends on biochemical effective dose values [16–19], the level of the radiation becomes

larger with increasing size of the prostate. Thus, this limitation is often hard to achieve in patients with a large prostate volume ( $>40$  ml) [20]. In such cases, androgen deprivation therapy (ADT) is used to reduce the prostate volume before brachytherapy [20, 21]. ADT is useful method for prostate volume reduction; however, ADT has a variety of adverse effects [22]. Avoiding ADT by using the undergarment may be beneficial for the patient with a large prostate.

There were several limitations in this prospective study. First, the statistical variations in the shielding rate were large, especially in the oblique directions, because of uncertainty in the measurements. Slight differences in measurement position may have occurred when the dose rate was measured with and without the protector, and the body thickness of patients can change dramatically in the oblique direction with just a small difference in angle. These factors caused variation in the measured dose rates. In addition, measurement uncertainties were higher since the boundary of protection wear varied between patient. The mean value of the dose rate with the protector measured in the oblique direction was  $0.38$   $\mu$ Sv/h, larger than that measured in the anterior direction ( $0.14$   $\mu$ Sv/h) (Fig. 4). Second, we examined only  $^{125}\text{I}$  seeds;  $^{103}\text{Pd}$  is not allowed in Japan. However, several papers have shown that the radiation exposures from patients with  $^{103}\text{Pd}$  are lower than those from patients with  $^{125}\text{I}$  [3–5]. In addition, the weighted mean photon energy from  $^{103}\text{Pd}$  is 21 KeV. The shielding rate for the lower photon energy of

$^{103}\text{Pd}$  would be theoretically higher than that for  $^{125}\text{I}$  (28 KeV). Third, we did not compare the shielding ability between the TFP-based undergarment and the lead-based undergarment. Hanada *et al.* reported that the lead-based undergarment can attenuate ~95.8% of the exposure rate in the anterior direction [7], and the shielding ability of the TFP undergarment is expected to be comparable with that of the existing lead-based undergarment. The lack of detailed data regarding the shielding ability of the lead-based undergarment makes it difficult to directly compare it with the TFP undergarment. However, it is clear that TFP is superior to lead in terms of reduced environmental toxicity, and we suggest that this justifies tolerance of any small difference in shielding ability between the TFP and the lead-based undergarment.

### CONCLUSIONS

In this prospective study, the shielding ability of a tungsten paper undergarment for patients with PSI was assessed. Our data showed ~90% reduction of the radiation exposure from the anterior and posterior directions. The undergarment (which has novel characteristics, including lead-free material and recycling ability) seems highly useful as a shielding material for patients with PSI.

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### CONFLICT OF INTEREST

Hajime Monzen has a consultancy agreement with and financial interest in Toppan Printing Corporation (Tokyo, Japan).

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