MYU Tokyo

S & M 3891

Development and Evaluation of Educational Systems Using Airborne Tactile Technology for Medical Radiation Protection

Daisuke Fujise,[1,2*] Yusuke Koba,[1] Shin Hasegawa,[1] and Toru Negishi[2]

[1]National Institutes for Quantum Science and Technology,
4-9-1 Anagawa, Inage-ku, Chiba-shi, Chiba 263-8555 Japan
[2]Division of Radiological Sciences, Faculty of Health Sciences, Tokyo Metropolitan University,
7-2-10 Higashiogu, Arakawa-ku, Tokyo 116-8551 Japan

(Received November 1, 2024; accepted December 16, 2024)

Keywords: radiation protection, aerial haptics, airborne ultrasound tactile display, mixed reality

In the medical field, the use of radiation for examinations and treatments offers the advantage of minimal invasiveness. However, exposure to excessive amounts of radiation can result in adverse effects commonly referred to as radiation damage. This issue is not exclusive to patients; it also affects medical professionals, including physicians, nurses, and radiology technicians. Therefore, it is imperative for medical professionals to receive comprehensive education on radiation protection. To enhance awareness of radiation protection, some studies have employed mixed-reality technology to render invisible radiation visible. However, only a few studies have employed alternative methods. In this study, we developed software that employs airborne haptics technology to deliver a tactile vibration to the user's hand upon finger contact with a virtual 3D model of primary X-rays, thereby signaling the position of the primary X-rays. To assess the software, 16 individuals (radiology technicians, educators, and students) were invited to experience the software and complete a questionnaire. The results of the questionnaire survey indicated that the software was perceived to be as useful as the previously developed visualization software. Additionally, it was confirmed that a potential exists for improvement in the application of vibrations to the palm.

1. Introduction

1.1 Issues in radiation protection education for medical professionals

Radiation is frequently used in numerous medical examinations and treatments.[(1,2)] In Japan, the number of such applications has been increasing annually.[(3–5)] The most common examinations and treatments involving radiation include computed tomography (CT), radiography, and interventional radiology (IVR), which are fluoroscopic examinations or treatments performed within the patient's body.[(6)] Radiation-based examinations and treatments are employed in a range of medical fields because of their minimally invasive nature compared with surgical procedures. However, excessive radiation exposure can adversely affect the

*Corresponding author: e-mail: fujise.daisuke@qst.go.jp
https://doi.org/10.18494/SAM5418

ISSN 0914-4935

human body, including dermatological issues. Consequently, patients and medical professionals, including physicians, nurses, and radiology technicians, must exercise caution to ensure safe radiation exposure during examinations and treatments.

The radiation generated by the CT, X-ray, and IVR angiography systems is produced using X-ray tubes. This radiation is referred to as primary X-rays. The region traversed by primary X-rays, known as the irradiation field, possesses a high spatial dose that can cause skin damage if fingers inadvertently enter the irradiation field during a procedure, leading to excessive radiation exposure. In the field of orthopedics, there have been reports of chronic exposure of the medical personnel's finger that enter the irradiation field, resulting in a high incidence of chromosomal abnormalities, skin lesions, and cancer resections.[7–9]

Radiation, being a form of electromagnetic wave rather than visible light, cannot be perceived by the naked eye when it is being irradiated for examination or treatment. Consequently, maintaining constant awareness of the irradiated area is challenging. In the field of radiation protection, it is of paramount importance for medical personnel who perform procedures to be fully aware of the irradiation area and to ensure that their hands and fingers remain outside the irradiation field at all times. In Japan, radiation protection education is provided to physicians, nurses, radiology technicians, and other medical personnel who handle radiation. However, it is challenging to assert that all medical personnel receive sufficient training and are highly aware of radiation protection.[10] Consequently, a clear need for effective radiation protection education exists.

1.2 Applications and issues of information technology in radiation protection education

Various methods have been investigated to enhance awareness of radiation protection. Because radiation cannot be perceived by the human eye, recent studies have concentrated on the visualization of radiation using virtual reality (VR) and mixed reality (MR) technologies, with the objective of implementing them in the field of radiation protection education. In a study conducted by Nishi *et al.*, [11,12] the distribution of scattered radiation was superimposed on the real world using smartphones and tablets, indicating that this approach has the potential to enhance the effectiveness of radiation protection education. Guo *et al.*[13] and Takata *et al.*[14] described the development of software using Microsoft HoloLens 2 (Microsoft Corp., Redmond, WA, USA) as a method employing a head-mounted display (HMD). In a previous study, we developed software to visualize the radiation dose in air using HoloLens2 and verified the utility of the software, confirming its practical applicability.[15] These represent efforts to render invisible radiation perceptible through visualization. Although visual recognition of radiation would be advantageous, all these approaches are limited to this single method, with minimal efforts made to explore alternative solutions. Moreover, the visual approach remains confined to the virtual space or is superimposed on the actual field of view, necessitating that the learner either holds a device such as a smartphone, tablet, or HMD in their hand or wears it on their head. As these devices superimpose radiation on the field of view, they impede the user's ability to manipulate radiation devices in the real world and perform detailed tasks. Consequently, it is challenging to educate students using a visual approach to gaining awareness of the fundamental aspects of radiation protection, such as the manner in which radiation traverses the body and interacts with other procedures and tasks, as observed in actual clinical practice.

Aristotle's theory of the soul posits that humans perceive their environment through five primary senses: sight, hearing, taste, smell, and touch. Given that the human body is susceptible to radiation, which can damage the exposed areas, it seems reasonable to suggest that the ability to perceive radiation as a tactile sensation is an evolutionary adaptation.

1.3 Application of tactile transmission technology

Research on perception and manipulation based on the human sense of touch has been conducted since the early 20th century. Attempts have been made to reproduce the feeling of touching virtual objects generated by computers.(16) Technology designed for haptic rendering has been developed (17,18) and implemented in the domain of education and learning.(19)

One category of haptic rendering is airborne haptics technology,(20,21) which can provide tactile sensations via ultrasound on the surface of the human body without the need for any attachments. An overview of this technology is presented in Fig. 1.

Ultrasonic waves are generated by multiple speakers to create a space in which ultrasonic waves resonate at arbitrary locations in the air. When the hand is positioned in that area, it perceives a tactile sensation. Although still in their infancy, devices using this technology can simulate the feel of buttons and sliding bars in the air.(22) It is expected to be used for noncontact game operations, car air-conditioning control, and other applications. In this study, we used airborne haptics technology for the tactile representation of radiation.

1.4 Motivation and objective

The overarching objective of this study is to develop a methodology for detecting radiation using nonvisual means. The ultimate goal is to create a system that can be utilized to advance radiation protection education and awareness for medical professionals who handle radiation. In this study, we examined a mechanism for perceiving radiation as a tactile sensation and confirmed its usefulness for educational purposes.

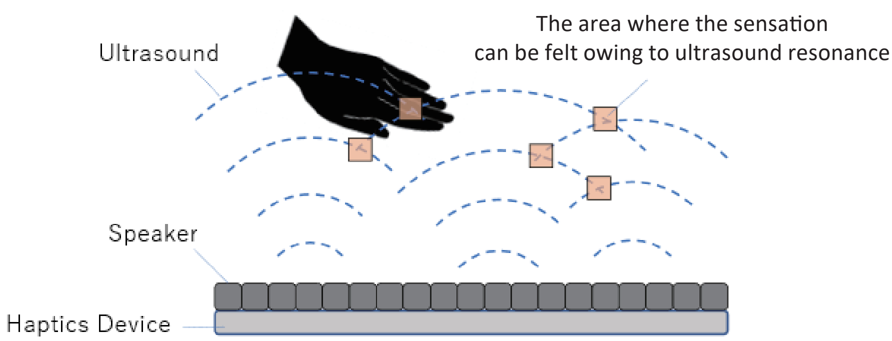

Fig. 1. (Color online) Overview of aerial haptics technology.

2. Materials and Methods

2.1 System overview

In this study, the developed radiation visualization system was extended to incorporate a tactile perception device to confirm the efficacy of haptic perception in the vicinity of a radiation source. The radiation visualization system generates a digital representation of the IVR angiography device and the human body within a virtual environment, which can be used to display the primary X-rays produced by the device. Furthermore, the software can be used to visualize the spatial radiation dose by loading in advance data that simulate the scattered radiation generated by primary X-rays. Utilizing the model of primary X-rays employed in this system, we develop a system that provides a tactile sensation to the user's hand upon contact with primary X-rays while simultaneously notifying the user of potential hazards. The proposed system employs an HMD we developed, which can be used to visually identify the location of primary X-rays (Fig. 2).

2.2 Environment development

Airborne haptics technology was implemented in this system using the STRATOS Explore and LeapMotion Controller (Ultraleap, Bristol, United Kingdom) (Fig. 3). The STRATOS Explore is equipped with a 256-speaker array arranged in a 16 × 16 configuration. The LeapMotion Controller employs an infrared camera to ascertain the three-dimensional position of the human hand. The combination of these two features enables the LeapMotion Controller to recognize the position of a person's hand and generate ultrasonic waves from the speaker to

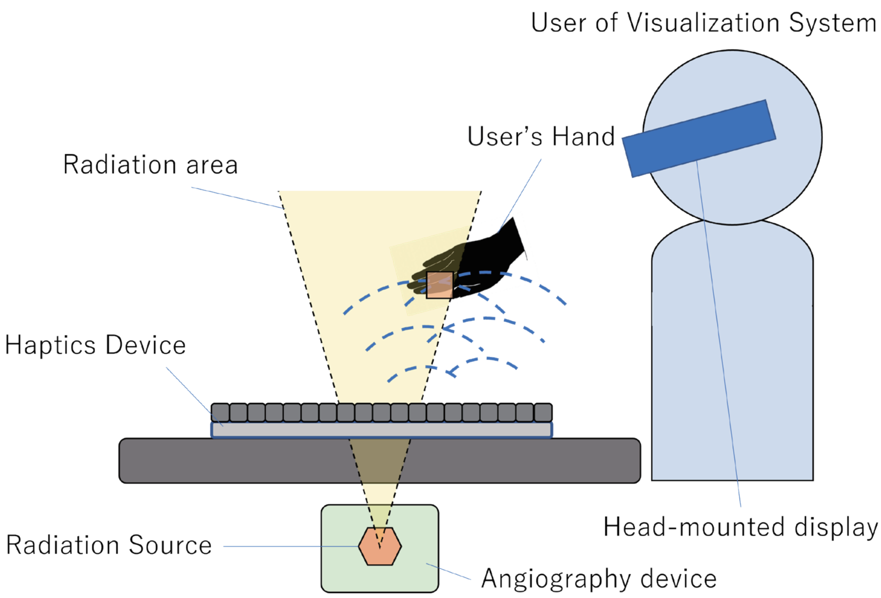

Fig. 2. (Color online) : Schematic of the system.

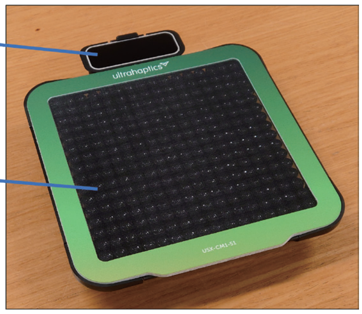

Fig. 3. (Color online) STRATOS Explore, LeapMotion Controller.

vibrate the air in accordance with the position of the hand, thereby allowing the user to perceive a tactile sensation in the air.

The STRATOS Explore and LeapMotion Controller can be used in conjunction with a computer operating on the Windows 10 platform. Version 4.0.0.0 was utilized to establish a connection with the aforementioned devices. Unity software, version 2018.4.9f1, was used to develop the associated software. Leap Motion Core Version 4.4.0 and the Ultrahaptics Core Asset for Unity, version 1.0.0-beta9, were also utilized.

2.3 Model design

The model comprises an angiography device utilized in IVR and a 3D human body phantom. The model is configured such that a radiation source is positioned beneath the bed, with primary X-rays emitted from beneath the bed and directed toward the patient. A model was constructed above the patient to simulate a detection plate that detects radiation, with radiation emitted toward the detection plate (Fig. 4).

2.4 System development

The system was constructed using the Unity platform and incorporated models, STRATOS Explore and Leap Motion Controller, for operational purposes. The system is designed to detect when the primary X-ray model is touched by a hand, as detected by the LeapMotion controller. Upon detecting the hand, STRATOS Explore generates ultrasonic waves to provide a circular tactile sensation at the center of the palm of the hand being detected. The hand position is continuously monitored as long as it remains within the detection range of the controller. This ensures that even if the hand is moved while in contact with the primary X-rays, a circular tactile sensation persists in the hand. Conversely, if the hand moves away from the primary X-rays, ultrasound generation is terminated and no tactile sensation is provided.

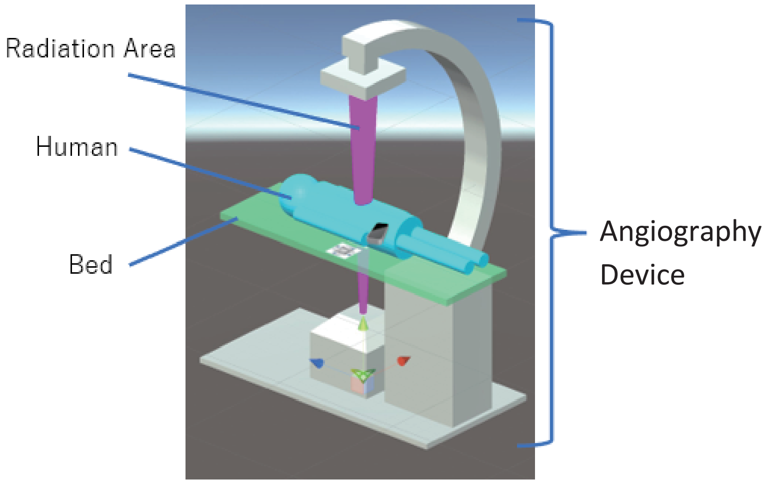

Fig. 4. (Color online) Model diagram.

3. Results

3.1 Evaluation of systems using airborne haptics technology

The proposed system has been shown to be capable of detecting the hand and providing a tactile sensation to the palm of the hand of the user when the hand comes into contact with the range of primary X-rays. Furthermore, it has been demonstrated that the tactile sensation to the palm of the user's hand ceases when the user's hand exits the primary X-ray range.

Additionally, it was confirmed that this system can be utilized in conjunction with a radiation visualization system by aligning the AR markers utilized in the radiation visualization system with the position of the instrument (Figs. 5 and 6).

3.2 Methods and results of usefulness evaluation

A questionnaire was administered to evaluate user perceptions of the software's usefulness. To ascertain the usefulness of the methodology employing airborne haptics technology, the survey participants were provided with an opportunity to experience the system in advance. Subsequently, they were invited to respond to a series of questions pertaining to both the visualization system and the airborne haptics system, posed in a questionnaire format.

The questionnaire was administered via a web form subsequent to the system's utilization. Questions regarding usefulness were posed on a three-point scale using the Likert scale, whereas questions concerning the rationale for system ratings and suggestions for improvement of the software were posed in a free-response format. The Likert scale is widely used in questionnaire surveys to evaluate the extent to which respondents agree with statements presented to them, and it is also used to evaluate the usefulness of software.[23–25]

Sixteen healthcare professionals involved in radiation work, as well as teachers and students involved in radiation education courses, were asked to experience the system and cooperate in

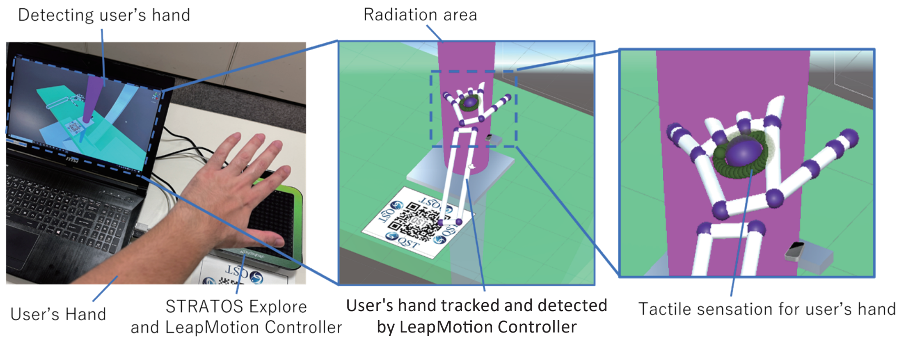

Fig. 5. (Color online) Working mechanism of the system.

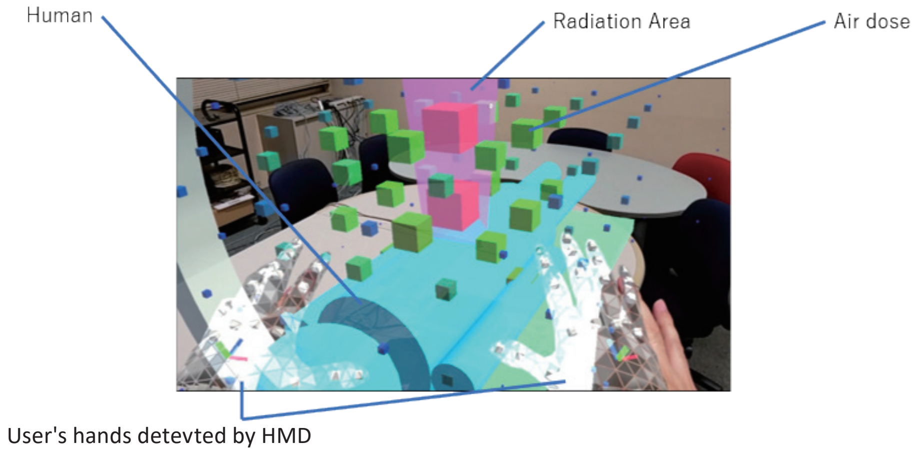

Fig. 6. (Color online) How user see using visualization system.

answering the questionnaire (Table 1). The respondents consisted of 11 radiology technicians, 2 teachers, and 3 students.

All 16 respondents completed the survey, and the results are presented below:

The usefulness of the radiation visualization software was evaluated as question 1-1, whereas systems employing airborne haptics technology was question 1-3. With regard to the radiation visualization system, 15 respondents answered “Agree”, one answered “Neutral”, and none answered “Disagree” (Table 2). As reasons for their answers, respondents who answered “Agree” for question 1-1 cited evaluation of usefulness, evaluation of safety, and educational benefits. However, one respondent answered “Neutral”, and no rationale for this answer was provided.

In the system utilizing airborne haptics technology, 14 individuals selected “Agree”, one individual selected “Neutral”, and one individual selected “Disagree” (Table 3). The respondents who selected “Agree” cited reasons that encompassed both the perceived usefulness of the technology and its potential for utilization in clinical settings. Additionally, they cited the anticipated functional enhancements as the rationale for their choices. Those who selected “Neutral” offered explanations related to the anticipated methodology of use. The sole respondent who selected “Disagree” highlighted that IVR does not assume direct exposure. However, the rationale behind this choice has not yet been established.

Table 1
Survey questions.

Section 1: Questions about the usefulness of the system		
Question number	Question	How to answer
1-1	Is the visualization of air dose (the ability to see air dose with your eyes) useful in radiation protection education?	Alternative Answers 1. Disagree / 2. Neutral / 3. Agree
1-2	Please indicate why you chose question 1-1.	Free-text entry
1-3	Is the direct ray tactile feedback (vibrating hands) system useful in radiation protection education?	Alternative Answers 1. Disagree / 2. Neutral / 3. Agree
1-4	Please indicate why you chose question 1-3.	Free-text entry
Section 2: How to represent spatial dose with tactile feedback systems		
Question number	Question	How to answer
2-1	Was the method of expressing air dose appropriate?	Alternative Answers 1. Disagree / 2. Neutral / 3. Agree
2-2	2-Please indicate why you chose 1.	Free-text entry
2-3	Please describe any information, features, or improvements that are missing from this software in the way spatial dose is expressed by the tactile feedback system	Free-text entry

Table 2
Answers to questions 1-1 and 1-2.

Answer	Number of people	Classification of reasons for selection	Summary of reasons for selection
Agree	15	Assessment of usefulness	- Easy to understand air doses as visual materials - Useful for understanding invisible things - Intuitive and easy to understand
		Safety assessment	- No real risk of exposure.
		Educational effect	- I felt that the awareness of visible radiation is different from that of invisible radiation.
Neutral	1	NA	NA
Disagree	0	NA	NA

Table 3
Answers to questions 1-3 and 1-4.

Answer	Number of people	Classification of reasons for selection	Summary of reasons for selection
Agree	14	Assessment of usefulness	- A method that uses the sense of touch is rare and interesting.
		Potential for clinical use	- It would be interesting if it could be used in a clinical setting.
		Improved functionality	- Weak tactile strength.
Neutral	1	Anticipated usage	- IVR does not assume direct ray exposure.
Disagree	1	NA	NA

Question 2-1 examined the suitability of the methodology employed to represent the air dose in systems utilizing airborne haptics technology. Question 2-2 substantiated the rationale for selecting this methodology.

Of the respondents, 11 selected “Agree” with the statement, citing their assessment of the notion and its articulation as the basis for their affirmation. However, although these respondents indicated that they selected “Agree,” functional improvement was also identified as a contributing factor (Table 4).

Four individuals selected “Neutral,” all of whom cited functional improvements as the rationale for their choice. The rationale provided was the need for precise vibration at the points of contact between the hands and the primary X-rays, together with the assertion that the range of tactile sensations was insufficient.

One respondent selected “Disagree,” citing a preference for a visualization system. However, the rationale for this preference was to improve functionality.

For Question 2-3, the respondents were invited to suggest additional features and improvements to the system. The responses provided opinions regarding functional improvements and safety considerations, as shown in Table 5. Regarding functional enhancements, the respondents expressed their opinions regarding the difficulty in recognizing hands, minimal vibration, necessity for a vibration intensity adjustment contingent on the dose level, importance of localized vibration to the hand contact point with primary X-rays, and provision of diverse irradiation patterns. From a safety perspective, some studies have highlighted the importance of providing alerts when the hand is on the verge of contact with primary X-rays.

Table 4
Answers to questions 2-1 and 2-2.

Answer	Number of people	Classification of reasons for selection	Summary of reasons for selection
Agree	11	Idea evaluation	- Very good idea!
		Evaluation of tactile sensation	- Tactile sensation is interesting - Easy to understand
		Improved functionality	- It would be interesting if it could be used in real time.
Neutral	4	Improved functionality	- The range of tactile sensation was small.
Disagree	1	Improved functionality	- It would be better to add green or color to the areas that indicate a certain level of air dose.

Table 5
Answers to questions 2–3.

Classification of answers	Summary
Improved functionality	• It was sometimes difficult to recognize hands • Vibration was too weak to be noticed • It would be easier to realize the degree of danger if the intensity of the vibration changed with the distance and dose • Various irradiation patterns should be vibrated to pinpoint the exposed area
Safety considerations	Alerts you when you are about to be exposed to primary X-rays

4. Discussion

Previously, the majority of studies have been conducted utilizing MR technology as an application of information technology in radiation protection education because radiation is invisible and cannot be directly perceived by the human eye, and invisible radiation has a high affinity with MR technology, which can add information to real space. However, with the advent of airborne haptics technology, it has become possible to achieve tactile recognition rather than visual recognition. In this study we developed a system that detects the presence of a hand within the range of primary X-rays and provides a vibration warning to the hand, although this is only effective within the primary X-ray irradiation field. This system is a new approach that has not been tried before, and we evaluated its usefulness by comparing it with visual methods.

In this study, we also developed a new system that can visualize primary X-rays using MR technology and simultaneously provide tactile feedback when the hand comes into contact with the primary X-ray area. We demonstrated that it is possible to perceive danger in a different way from visual methods. The utility of the system was evaluated, confirming the usefulness of both the radiation visualization system and the system employing aerial haptics technology using the Likert scale. The Likert scale is used for evaluation and measurements in a variety of fields, including software evaluation. In this study, we conducted a quantitative evaluation using a questionnaire to evaluate the usefulness of a system developed using the Likert scale. Fifteen individuals indicated that the radiation visualization system was "useful," whereas 14 individuals indicated that the system utilizing aerial haptics technology was "useful." The outcomes were predominantly comparable, confirming that the system employing aerial haptic technology was equally effective as the radiation visualization system. This system is believed to be an effective method of education on radiation protection.

However, several areas of improvement were identified. Although the use of vibrations to recognize primary X-rays is an effective method for alerting the user to potential dangers, one area for improvement in this system is that the vibration is consistently localized to the palm, which does not correspond to the actual location of the hand's exposure to primary X-rays. To enhance the intuitiveness of the system, it will be essential to refine it in the future by calibrating the vibration range to align it with the actual position where the hand is exposed to the primary X-rays. Furthermore, although airborne haptics technology has been utilized in virtual environments for IVR, the risk of direct radiation exposure in IVR is relatively minimal. Consequently, it is imperative to consider irradiation patterns as a means of radiation protection education, particularly in the context of orthopedic surgery and other pertinent fields.

There are some improvements in the system we proposed. The LeapMotion Controller, which is a device that composes the haptic device used in this study, has been reported to have an accuracy deviation of 1.2 mm.[26] In addition, the system we proposed can detect only one hand, At this moment, even if two hands are in the irradiation field, feedback can only be given for one hand. Therefore, some improvements will be required for displaying the position of the AR marker position on the MR and detecting the user's right and left hands in the future work.

5. Conclusions

In this study, we developed software for medical personnel that serves as an educational tool for radiation protection. The software utilizes airborne haptics technology to notify medical personnel of potential dangers by vibrating their hands when they encounter primary X-rays. This extends the developed radiation visualization system. The developed software can be utilized in conjunction with visualization software. Upon contact between the palm and the 3D model of the primary X-rays, a vibration is generated at the center of the palm, which serves as an alert to potential dangers. The utility of the software was assessed using a questionnaire, which indicated that the software was as beneficial as the visualization software. Conversely, the questionnaire identified several areas for improvement in software functionality as a radiation protection educational tool. These shortcomings will be addressed in future iterations of the software to enhance its effectiveness as a radiation protection educational software program.

This study also corroborates the hypothesis that the tactile perception of radiation may be an effective method for raising awareness of radiation protection. Unlike MR visualization, it does not impede the user's actual working field of vision, thus facilitating the realization of clinical applications that allow awareness of actual radiation, thereby reducing occupational exposure. It is anticipated that this will lead to the realization of clinical applications that will allow users to become aware of actual radiation and reduce occupational exposure. Therefore, further research is necessary.

6. Limitations

This study has potential limitations. The LeapMotion Controller, which is a device that composes the haptic device used in this study, has been reported to have an accuracy deviation of 1.2 mm, and it has the potential to deliver vibrations to the hands when they encounter primary X-rays, and the accuracy depends on the performance of the hardware and controller drivers. In addition, there is a possibility that the position relationship with the primary X-rays will be shifted owing to the deviation in the position of the AR marker. The system we proposed can detect only one hand.

Acknowledgments

The software was evaluated with the assistance of 16 radiological technologists, faculty members, and students engaged in radiation technology and radiation education courses. We express our sincere gratitude to the reviewers.

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