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Shape memory alloy (SMA)-based head and neck immobilizer for radiotherapy

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Abstract

Head-and-neck cancer is often treated with intensive irradiation focused on the tumor, while delivering the minimum amount of irradiation to normal cells. Since a course of radiotherapy can take 5–6 weeks or more, the repeatability of the patient posture and the fastening method during treatment are important determinants of the success of radiotherapy. Many devices have been developed to minimize positional discrepancies, but all of the commercial devices used in clinical practice are operated manually and require customized fixtures for each patient. This is inefficient and the performance of the fixture device depends on the operator's skill. Therefore, this study developed an automated head-and-neck immobilizer that can be used during radiotherapy and evaluated the positioning reproducibility in a phantom experiment. To eliminate interference caused by the magnetic field from computed tomography hardware, Ni – Ti shape-memory alloy wires were used as the actuating elements of the fixtures. The resulting positional discrepancy was less than 5 mm for all positions, which is acceptable for radiotherapy.

Keywords: Radiotherapy; Shape memory alloy; Immobilizer; Head and neck cancer; Prototype

1. Introduction

In Korea, 50–60% of cancer patients can potentially undergo radiotherapy and 25–30% of them have received actual radiotherapy. Modern radiotherapy methods use an intensive irradiation strategy that maximizes the irradiation of cancer cells, while minimizing the dose to normal cells. The recent improvements in radiotherapy have been due mainly to the development of hardware and software associated with radiotherapy devices, and the development of state-of-the-art treatment equipment for radiotherapy will increase the effectiveness of cancer treatment.

For head-and-neck cancers, the irradiation gradient requires a steep dose fall to minimize the unnecessary irradiation of normal areas because the major organs are densely packed in this region and these organs are very sensitive to radiation. Therefore, when head and neck cancer patients receive radiotherapy, if the patient's posture is not reproduced accurately within a few mm of the previous treatment, the tumor is not exposed to sufficient prescription doses and normal organs are simultaneously exposed to high radiation levels. This can impair normal organ function and, in extreme cases, kill the patient. Since a course of radiotherapy can take 5–6 weeks or more, the repeatability of patient posture and the fastening method used during treatment significantly affect the success of radiotherapy. Therefore, the use of an immobilizer for radiotherapy for head and neck cancer is essential, and various

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commercial devices are used to maintain the same posture during the repeated treatments.

The common head-and-neck immobilizer currently used in medical area is shown in Fig. 1. To hold and maintain exact position during irradiation, a net-shaped mask made of thermoset plastic is molded conforming the face of the every patient. This mask not only fixes the head-and-neck not to wander from initial position during treatment by covering front face or neck of the patient laying on table for radiotherapy, but also helps to reproduce the same position in subsequent treatment after several days later during entire radiotherapy period. Because this fastening method with a net-shaped mask requires a specially designed disposable fixture for every patient, however, it consumes too much material and causes difficulty in storing those masks in the hospital facility. Patients often suffer uncomfortable feeling or sometimes fear due to the mask that blocks patient's view during overall treatment time and clinicians feels annoyingness because of the mask that should be re-made every treatment.

In terms of treatment efficiency, the mask can be considered as an obstacle that disturbs path of radiation, and this leads to different dose rate when it is compared with irradiation simulation of dose rate at the tumor. Even more, most patients undergo significant weight loss and change of facial form, which causes empty space between the previously used thermoset mask and the patient's head. This positional errors should be minimized during the entire course of therapy.

2. Related studies

Modern fractionated radiation therapy is based on the ability to immobilize the patient in a reproducible position. This is particularly important for patients with tumors adjacent to important normal intracranial and head-and-neck structures. For these patients, various immobilizers are used, and many studies have examined techniques to minimize geometrical discrepancies [1–6]. Bentel et al. [1] describe a customized headrest to support the posterior head and neck. Quantitative analysis results show that the customized support is better able to address variability in patient shape. The work of Laing et al. [7] reported that the geographical miss of the immobilizing system with stereotactic frame varies from 0.3 to 2.3 mm, excluding the CT scan uncertainty. Shim et al. [5] proposed an adjustable holder for head-and-neck cancer patients to fix the patient's position and evaluated the geometrical discrepancies when performing radiotherapy in terms of the relationship between patient's weight and the range of error through comparison of differences between computed tomography (CT) and cone beam computed tomography (CBCT) images. These previous studies mainly claim that the newly developed immobilizing method gives better performance for keeping the same head-and-neck position within acceptable ranges. However, because these devices are still operated manually or require customized fixtures for each patient, they are not only inefficient for both of patients and clinicians, but also highly dependent on operator's skill to achieve sufficient treat performance.

This study developed an automated head-and-neck immobilizer driven by the contraction force of shape-memory alloy (SMA) wire. Conventional actuators, such as those using electric motors, are applied for automation equipment because of their high accuracy, simple control method and long life. However, these kind of conventional actuators can malfunction on exposure to radiation and the bulky metallic parts disperse the radiation, attenuating the effect of radiotherapy. To overcome the limits of standard actuators, we developed a simple, unique mechanism that makes use of the contractile force of an SMA. SMA has two stable solid phase microstructures, austenite and martensite. When the SMA is heated, it can provide mechanical force to transform from martensite to austenite. By adopting this force in an actuation system, we can design a device which has small and simple structure, different from conventional actuators because SMA itself can work as an actuation part and does not requires any additional apart to generate actuation forces. SMA actuators are effective because they can generate high actuation forces and maintain a deformed shape when heat is applied [8]. More importantly, SMA wire interferes little with the radiation environment; i.e., electromagnetic field, compared with motor and gear-based mechanisms [9].

3. System configuration of the prototype

The prototype consists of three main parts: (1) a central head holder; (2) a point-type head fixation device; and (3) an adjustable pillow behind the head. The computer-aided design (CAD) is shown in Fig. 2. Each part is designed to satisfy a specific purpose. To minimize barrier objects in the radiation path, all of the components, except essential structures and the end effecter, are located in non-irradiated areas. The immobilization process is

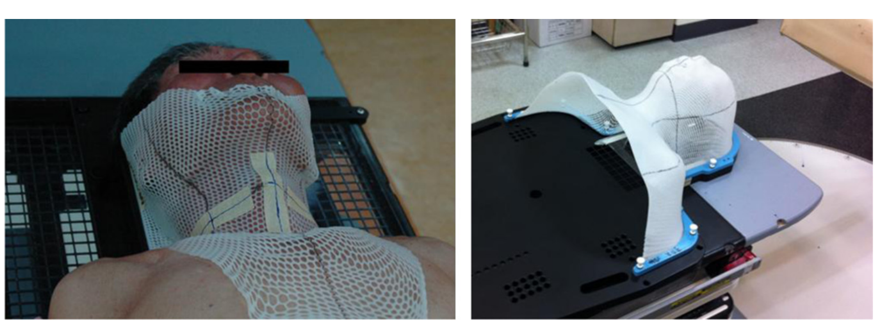

Fig. 1. Pictures of conventional head and neck holder mask used for radiotherapy surgery.

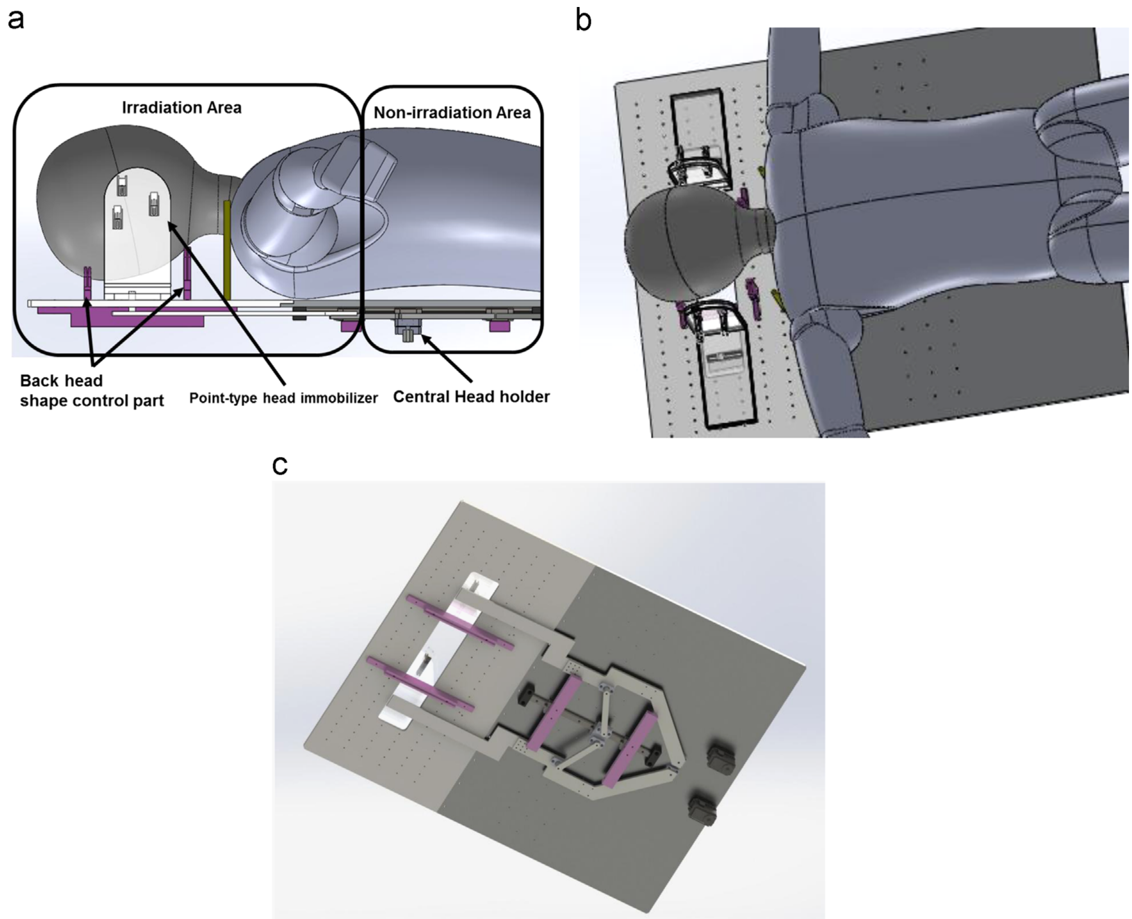

Fig. 2. (a) Composition of head and neck immobilizer and overall view from (b) front and (c) back side of CAD model.

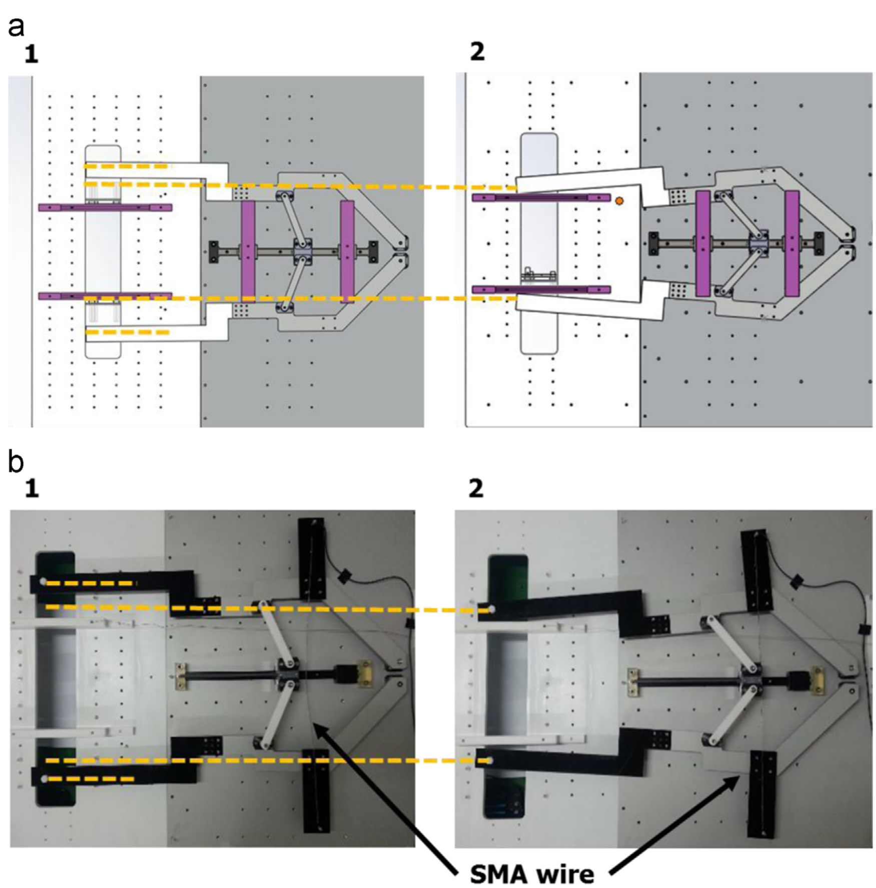

Fig. 3. Comparison of (a) CAD modeling and (b) actual test of the central head holder before and after gripping motion by contraction of SMA wire.

as follows. First, the back of the head is controlled using the adjustable pillow to fit the shape of the patient's head. Then, the head and neck are gripped using the central head holder to keep the head centered on the table. Finally, the point-type head fixator is tightened to prevent the head from translation or rotation during the radiotherapy. The information of the geometric location of each patient's head is stored and the same information is loaded during subsequent treatments to reproduce the same position. The detailed working mechanism of each part is described in the following paragraph.

3.1. Detailed design of the immobilizer

1) A central head holder: The central head holder is designed to prevent posture error in the transverse direction. It helps the end effectors to grip the head and maintain a central position during treatment. The gripping motion is driven by the contraction force of the SMA wire. Each end of the wire is connected one third of the way along the arms of this big ‘gripper’, which is placed behind the table. With this design, we can move the actuating parts out of the irradiated area and enlarge the stroke of the gripper, as the wire connection points act as the fulcrum of a lever. This can also compensate for the small contraction rate of the SMA wire, which is only 4% of the initial length, and results in gentler movement of the end effector. Both the simulation using the CAD model and the actual tests of the prototype described in Fig. 3 showed that it allows sufficient distance for head gripping and maintains the central position of the table. When the SMA wire is heated using an electric current, the wire contracts as a result of the shape memory effect, shortening the distance between the two end effectors, so that they grip the patient's head. Since the middle of the gripper's arms is linked by a guide rail located at the center of immobilizer, each arm moves symmetrically to keep the central position of the head.
2) A point-type head fixation device: A point-type head fixator was attached at the end effector, to prevent head rotation

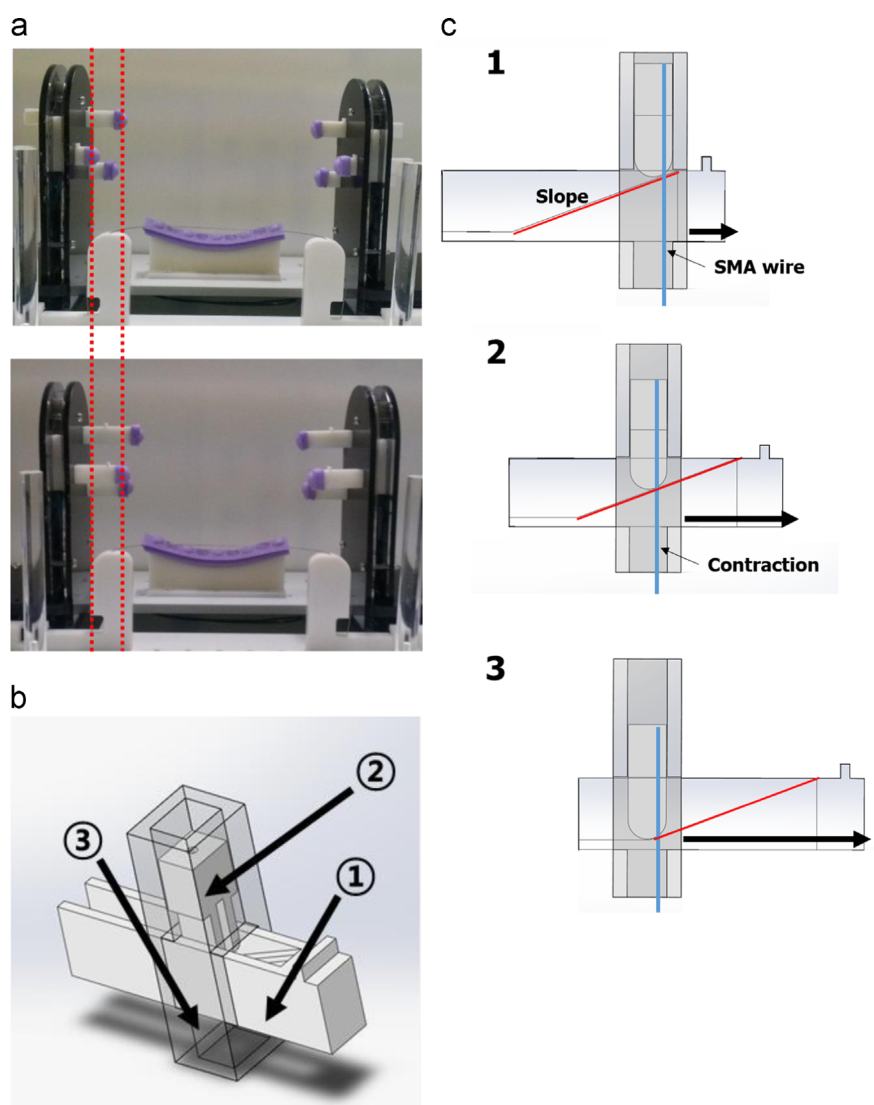

Fig. 4. (a) Manufactured prototype, (b) detailed component configuration of point-type head fix and (c) contraction-sliding mechanism of point-type head fix. (① pointer, ② upper bar and ③ SMA wire binder).

error and to grip the head more precisely. This part must function in the irradiation environment and an actuation mechanism based on shape memory is good for a compact high-output application [10]. As shown in Fig. 4, this fixator consisted of a ① pointer, ② upper bar, and ③ SMA wire binder. This simple structure consists only of thin metallic SMA wire and an ABS polymer that minimizes the dispersion of radiation. Once an electric current is applied to the SMA wire, the heat emitted from the wire causes it to shrink via the shape memory effect. The upper bar linked to the SMA wire pushes down the slope of pointer and each pointer moves forward as much as possible to fit the curvature of the side of the patient's head. This trigger mechanism with sloped structure helps to reduce pressure and generate moderate gripping force applied on the patient's head.

3) An adjustable pillow: The medical pillows currently used in radiotherapy are available only in three to five pre-shaped blocks, and these are unsuitable for fitting all possible head shapes. Consequently, the patients feel uncomfortable and the clinician often has trouble reproducing the exact location of the back of the head. The adjustable pillow proposed in this study uses thin steel wire and a motorized control to shape the pillow and achieve more precise

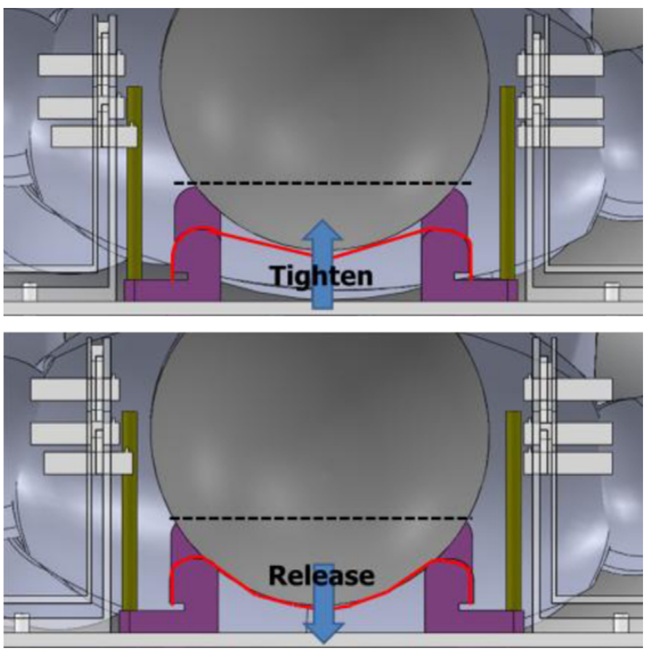

Fig. 5. Example of working mechanism of back head shape adjust pillow.

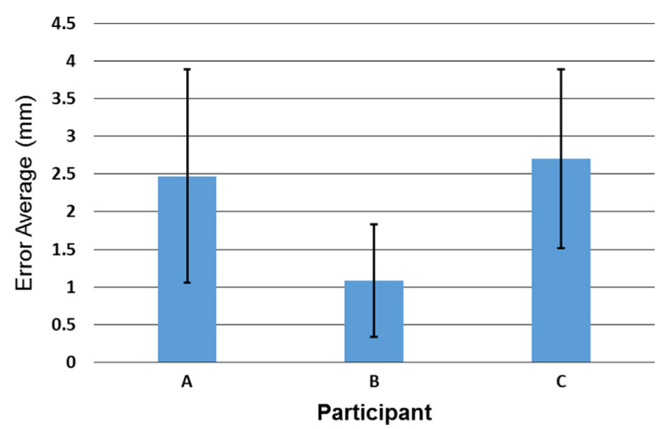

Fig. 7. Graphical results on geometrical discrepancies on repeated immobilizing test.

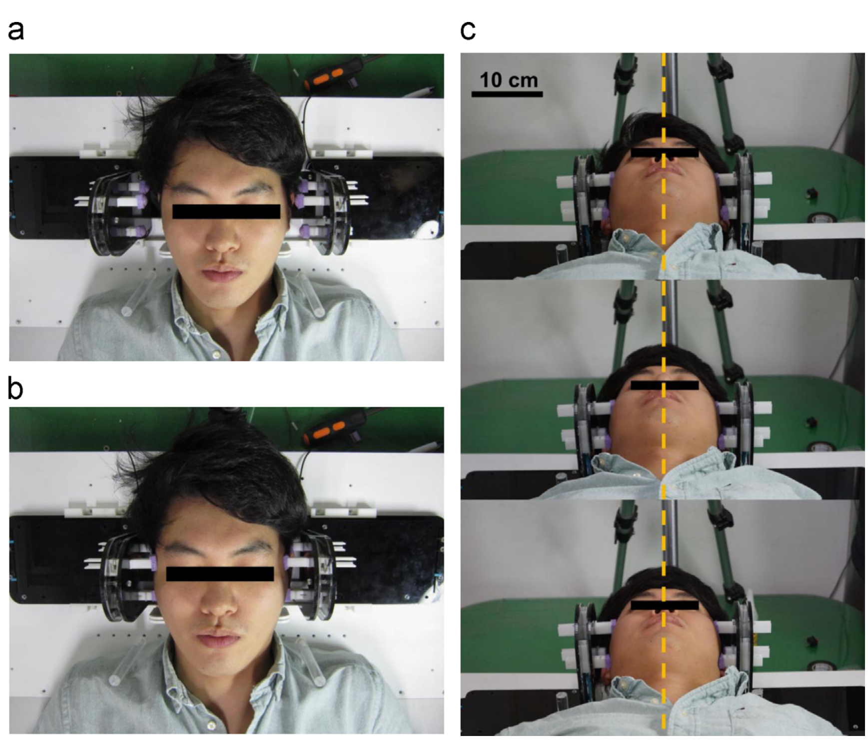

Fig. 6. Pictures of actual immobilizing test (a,b) and repeated test for evaluation of locational reproducibility.

reproducibility. The location of Servomotors located at the bottom of table control the length of the steel wire, to adjust the shape of the pillow for each patient. Two wires support the highest and lowest points of the back of the head, precisely controlling the position (Fig. 5).

4. Evaluation

Locational reproducibility of the proposed immobilizer is tested on normal participants. As shown in Fig. 6, a participant was laid down on the immobilizer prototype and fixed the head through the process described in previous section. The detail gripping conditions such as current applied on SMA wire of central head holder, length of still wires of adjustable pillow and offset distance from the bottom layer are memorized. Then, the operator releases the device and takes immobilizing process again by loading memorized conditions. For the same participant, this repeated process were tested several times, and geometrical displacements are measured by comparing the locations of a certain point of the head. The positional error was measured with three participants, and all of the geometrical discrepancies resulted in less than 5 mm (Fig. 7).

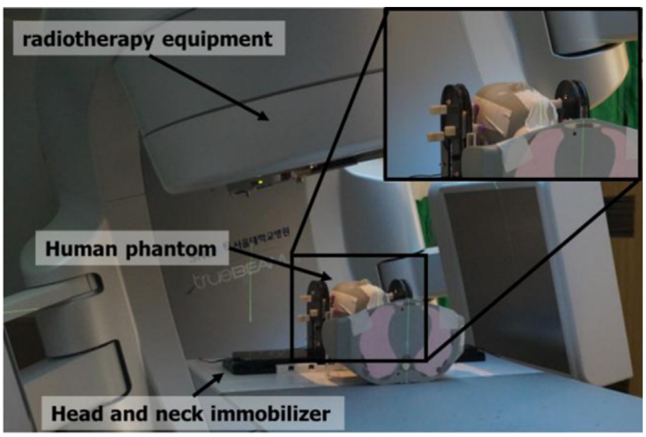

Fig. 8. Phantom experiment of the developed immobilizer in real radiotherapy equipment.

To evaluate the performance of the prototype in an actual radiation field, a phantom experiment was performed in a real radiotherapy device at Seoul National University Hospital (Fig. 8). Cross sectional images of a human phantom fastened by proposed immobilizer was obtained by using computed tomographic (CT) imaging system that is used to determine the dose rate before treatment. Then, the phantom moved to radiation therapy equipment used in actual treatment and cone beam computed tomographic (CBCT) images were taken. The CBCT images are also obtained while the phantom was fixed by the immobilizer developed in this research. Geometrical discrepancies of this CBCT images are measured by comparing with CT images. The CBCT and CT images were overlapped at each cross section and the consistency evaluated in terms of location and the curvature error (Fig. 9). The

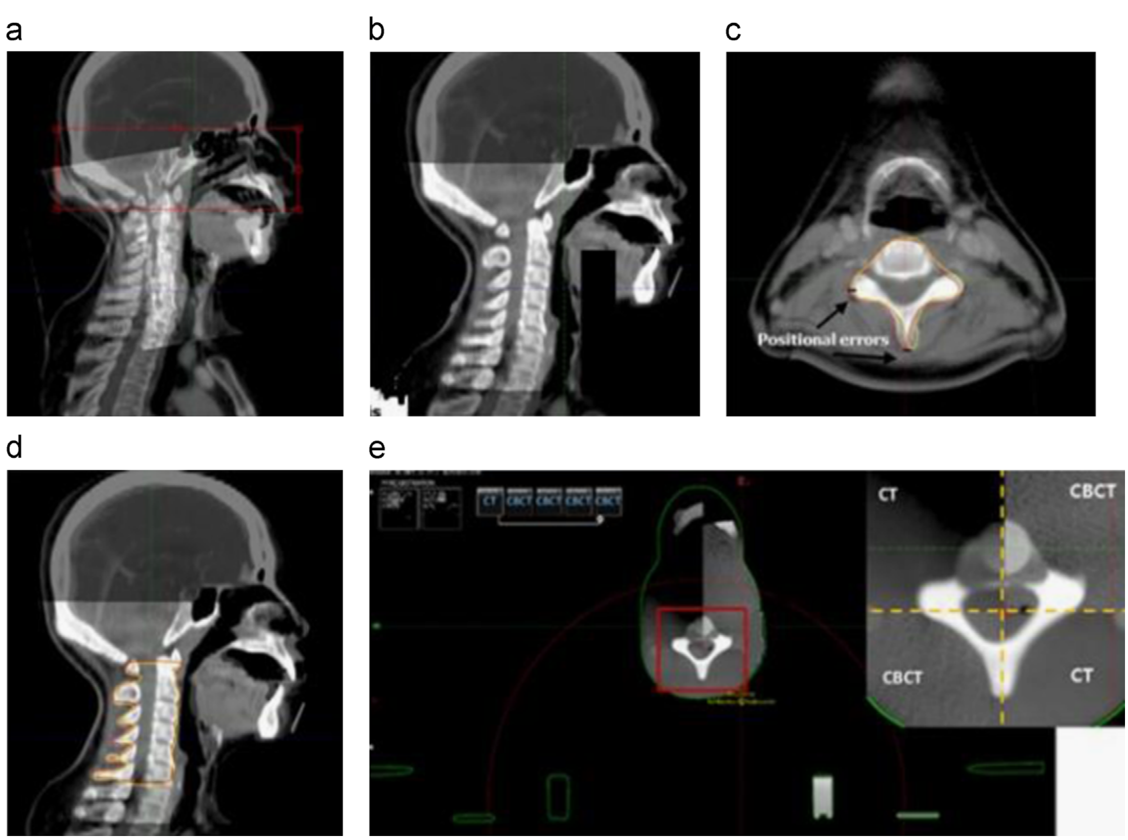

Fig. 9. Pictures of geometrical discrepancies evaluation process: First, stack the CT and CBCT images of human phantom fixed by developed immobilizer (a). Then, the pictures are aligned to match curvature lines of the patients head (b). The geometrical discrepancies are evaluated by comparing differences between CT and CBCT images (c – e).

calculated positional errors also showed less than 5 mm discrepancies in entire sections and this value is within the acceptable range for radiotherapy. Consequently, similar dose distributions are expected during actual radiation treatment when compared with the result calculated during radiotherapy planning.

5. Conclusions

This study developed an automated SMA-based head-and-neck immobilizer for radiotherapy. A simple actuation mechanism using SMA wires was developed as a substitute for conventional actuators to prevent the dispersion of radiation, which can have negative effects during radiotherapy. The spatial discrepancies between CT and CBCT images was evaluated the positional error results shown in both evaluation were within the acceptable range (5 mm) for radiotherapy. For future research, degradation factor on SMA wires in radiative environment will be investigated to guarantee repeatability of the proposed prototype.

Acknowledgments

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References

[1] Bentel, GC, et al. A customized head and neck sup-port system. *International Journal of Radiation Oncology Biology Physics* 1995;**32**(1) 245–8.

[2] Height, R, et al. The dosimetric consequences of anatomic changes in head and neck radiotherapy patients. *Journal of Medical Imaging and Radiation Oncology* 2010;**54**(5)497–504.

[3] Manning, MA, et al. The effect of setup uncertainty on normal tissue sparing with IMRT for head-and-neck cancer. *International Journal of Radiation Oncology Biology Physics* 2001;**51**(5)1400–9.

[4] Saw, CB, et al. Immobilization devices for intensity-modulated radiation therapy (IMRT). *Medical Dosimetry* 2001;**26**(1)71–7.

[5] Shim, J, et al. Development of adjustable head holder couch in H&N cancer radiation therapy. *The Journal of the Korean Society for Radiotherapeutic Technology* 2014;**26**(1)43–50.

[6] Thornton Jr A, et al. Three-dimensional motion analysis of an improved head immobilization system for simulation, CT, MRI, and PET imaging. *Radiotherapy and Oncology* 1991;**20**(4)224–8.

[7] Laing RW, Thompson V, Warrington AP, Brada M. Feasibility of patient immobilization for conventional cranial irradiation with a relocatable stereotactic frame. *The British Journal of Radiology* 1993;**66**(791) 1020–4.

[8] Kim H-J, Song S-H, Ahn S-H. A turtle-like swimming robot using a smart soft composite (SSC) structure. *Smart Materials and Structures* 2013;**22**(1)014007.

[9] Rodrigue H, Wang W, Bhandari B, Han M-W, Ahn S-H. Cross-shaped twisting structure using SMA-based smart soft composite. *International Journal of Precision Engineering and Manufacturing-Green Technology* 2014;**1**(2)153–6.

[10] Cho K-J, Koh J-S, Kim S, Chu W-S, Hong Y, Ahn S-H. Review of manufacturing processes for soft biomimetic robots. *International Journal of Precision Engineering and Manufacturing* 2009;**10**(3)171–81.