Real-time Body Surface Motion Tracking using the Couch Based Computer-controlled Motion Phantom (CBMP) and Ultrasonic Sensor: A Feasibility Study

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Respiration gating radiotherapy technique developed in consideration of the movement of body surface and internal organs during respiration, is categorized into the method of analyzing the respiratory volume for data processing and that of keeping track of fiducial landmark or dermatologic markers based on radiography. However, since these methods require high-priced equipments for treatment and are used for the specific radiotherapy. Therefore, we should develop new essential method whilst ruling out the possible problems. This study aims to obtain body surface motion by using the couch based computer-controlled motion phantom (CBMP) and US sensor, and to develop respiration gating techniques that can adjust patients' beds by using opposite values of the data obtained. The CBMP made to measure body surface motion is composed of a BS II microprocessor, sensor, host computer and stepping motor etc. And the program to control and operate it was developed. After the CBMP was adjusted by entering random movement data, and the phantom movements were acquired using the sensors, the two data were compared and analyzed. And then, after the movements by respiration were acquired by using a rabbit, the real-time respiration gating techniques were drawn by operating the phantom with the opposite values of the data. The result of analyzing the acquisition-correction delay time for the data value shows that the data value coincided within 1% and that the acquisition-correction delay time was obtained real-time (2.34×10^{4} sec). And the movement was the maximum movement was 6 mm in Z direction, in which the respiratory cycle was 2.9 seconds. This study successfully confirms the clinical application possibility of respiration gating techniques by using a CBMP and sensor.

Key Words: Couch based computer-controlled motion phantom (CBMP), Respiration gating radiotherapy technique, Body surface motion, Sensor, Radiotherapy

INTRODUCTION

In the field of radiotherapy, the inter-fraction and intra-fraction reproducibility of tumor localization is important in making a treatment plan. Furthermore, it is a crucial factor for the improvement of treatment performance. To date, some factors have been reported to affect the reproducibility of tumor localization, which include the coincidence of individual anatomical landmarks, the inter-fraction change and intra-fraction movement of internal organs. Among these factors, respiratory movement is one of the major causes of the intra-fraction movement of internal organs.[1,2] In most cases of the upper abdominal tumors seen in such organs as lung or liver, the irradiation volume increases as tumors progress during respi-

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ration. As a result, the enhanced radiation toxicity renders normal tissue vulnerable to high-dose irradiation. In addition, the accurate localization of tumor is difficult since the patient's set-up is constantly varying. Accordingly, it is imperative that the state-of-the-art system be developed in such a manner as to concentrate high-dose irradiation to the target area by accurately localizing the lesion. To enhance the treatment performance, the movement of internal organs during respiration must be minimized. In other words, since the accurate localization of tumor is difficult, there is inconsistency between the tentative target area and the actual treatment site. This will eventually make the local tumor control unsuccessful. The greater the degree of errors in the patient's set-up is, the greater planning target volume will become than clinical target volume. As a result, normal tissue will be exposed more prevalently to high-dose irradiation. Therefore, it can be inferred that the possibility of normal tissue undergoing the complications will be markedly decreased by determining the target volume in serious consideration of not only the errors in the patient's set-up but also the movement of internal organs during respiration.[3-7]

Respiration gating radiotherapy technique developed in consideration of the movement of body surface and internal organs during respiration, is categorized into the method of analyzing the respiratory volume for data processing[8-13] and that of keeping track of fiducial landmark or dermatologic markers based on radiography.[14-19] Respiration gating radiotherapy technique to manage respiratory induced tumor motion during radiation delivery include breath-holds, beam gating and real-time tumor tracking. Tumor tracking can be either MLC-based or couch-based. Breath-hold and gating techniques pose the disadvantage of increased treatment time. And MLC-based tracking is limited in resolution in one direction by the leaf width.[20]

However, since these methods require high-priced equipments for treatment and are used for the specific radiotherapy. In particular, the method of analyzing the respiratory volume will be problematic since it requires the arbitrary control of respiration. Therefore, we should develop new essential method whilst ruling out the possible problems.

Under the background described above, we conducted this study to develop the new, versatile and accurate respiration gating radiotherapy technique that is customizable to a clinical setting in Korea. To do this, we acquired the movement of body surface using both couch based computer-controlled motion phantom (CBMP) and US sensor; and presented the new method (couch-based tumor tracking technique) that can optimize the bed using the reverse value of acquired data.

MATERIALS AND METHODS

1. The making of a CBMP

A CBMP was made to evaluate the body surface motion compensation during respiration. A CBMP consists of a controller (BS II, 20 MHz, 8 Kbyte), US sensor, a PC (RS232C) and a stepping motor (Torque 2.3 kg). To handle the data, a specialized program for acquisition, correction and analysis (Microsoft Visual studio 7.0, Microsoft Access) was created (Fig. 1). The purpose of developing this CBMP was to demonstrate the initial feasibility of the concept of couch- based inter-fraction motion compensation.

2. The characteristics of US sensor

In the present study, an ultrasonic sensor (SRF04 ultrasonic range finder, Parallax, USA) was used. This sensor emits an ultrasonic wave with a frequency of 40 kHz and an acquisition range of 3 cm ~ 3 m. A sensor module is composed of the part emitting a sound wave and that receiving a reflected sound wave. On receiving the trigger input of 10 μs in frequency, a sensor module emits a sound wave with a frequency of 8 cycles. Reflected from the object surface, a sound wave is recognized by the receiving part of an ultrasonic sensor. Then, the trigger input is again fed into a sensor module after 10 ms. These processes are repeated five times. The mean value of pulse is then calculated. Finally, the distance between the object and the sensor is numerically visualized in units of cm and inch.

3. A sensors data acquisition program for body surface motion

To acquire the sensor data, Basic stamp II microcontroller (MCU) 2.5 tool (Parallax, California, USA). This program is composed of Basic interpreter chip, internal memory (RAM and EEPROM), 5 V regulator, I/O pins (TTL-level) and command sets. The programming language is PBASIC. MCU is referred to as a machine-interface-type CPU (processor, I/O, memory) that connects between CPU and terminal. The contents of

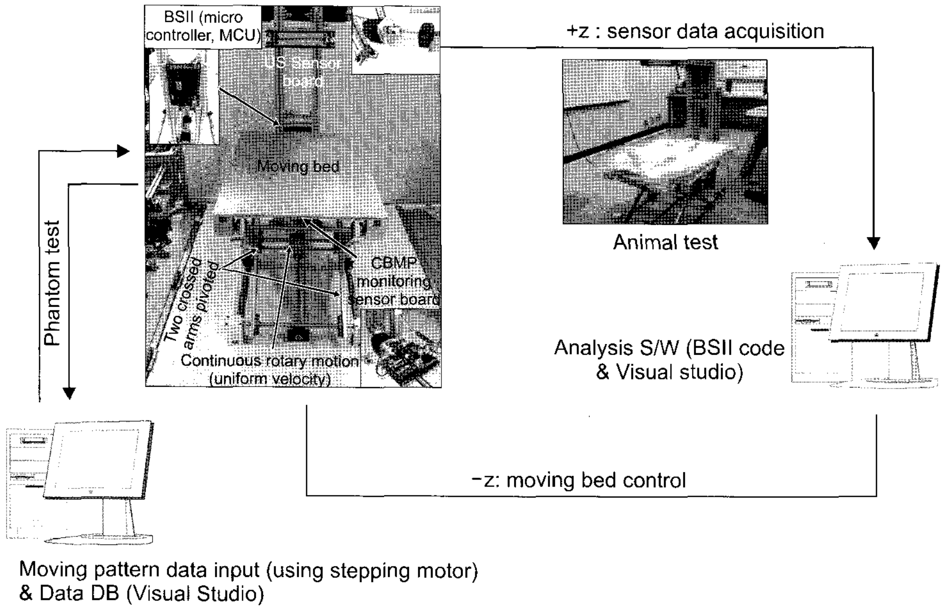

Fig. 1. A Schematic diagram of experimental process. The CBMP (couch based computer-controlled motion phantom) system consists of an custom made computer-controlled motion phantom for acquisition-correction of respiratory motion and a sensor (US). Host computer (RS232C) connected with the BS II (Basic stamp code) tool is used to data analysis. (Z; anterior-posterior).

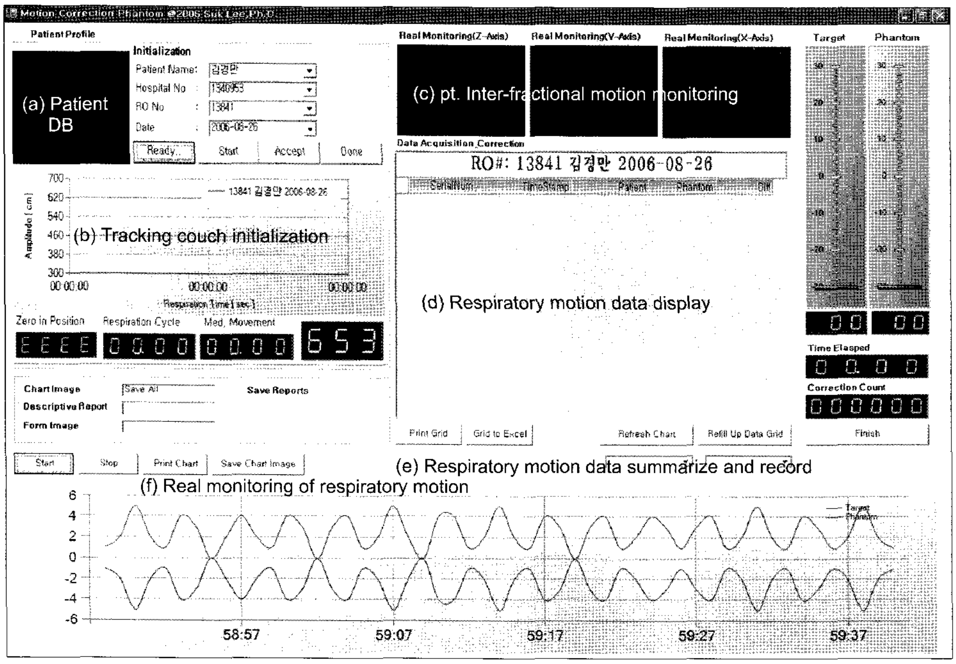

Fig. 2. It shows that an analysis of the acquisition-correction program: (a) patient DB, (b) tracking couch initialization, (c) pt. inter-fractional motion monitoring, (d) respiratory motion data display, (e) respiratory motion data summary and record, (f) real monitoring of respiratory motion.

program were created as the delay time for the acquisition of sensor data, patient DB, tracking couch initialization, patient inter-fractional motion monitoring, respiratory motion data display, respiratory motion data summarize and record and real monitoring of respiratory motion (Fig. 2).

4. A couch-tracking method for correction of body surface motion

A monitoring is done to compare the sensor data stored in the database at each time point. The bed is moved by using the opposite value of the sensor data until the data return to the

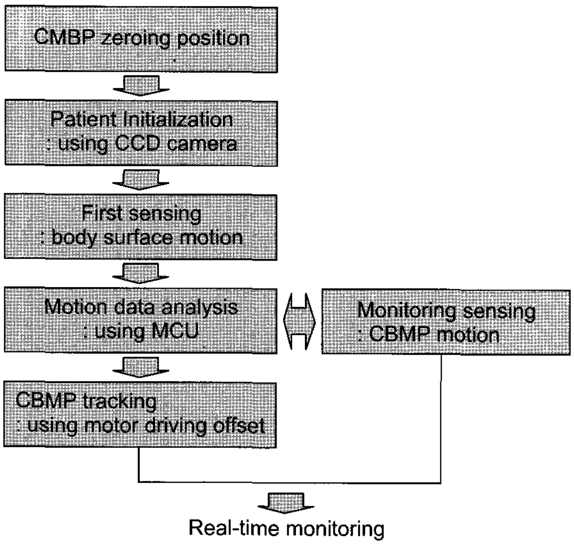

Fig. 3. It shows that real-time couch tracking and CBMP monitoring flow chart.

default. Mechanical movements of phantom are continuous rotary motion at a uniform velocity of the screw carrying the circular roller. And compound parallel rulers connected by two crossed arms pivoted together at the middle of their length, each pivoted at one end to one of the rulers, and connected with the other on linear rails. In this the ends as well as the edges are kept parallel. From the US sensor the data transmits the MCU (BS 24px), it compares them and figures out the compensating movements amount up and down and send it to the stepping motor (30 steps of one radian) make the motor rotate paced with a patient respiratory time. And Fig. 3 shows that real-time couch tracking and CBMP monitoring flow chart.

5. An acquisition-correction of data and its delay time: measurement and analysis

1) A measurement for an acquisition-correction of the sensor data

A program for an acquisition-correction of the sensor data was created, which included the following: (1) the part representing the coordinate value that makes it possible to ascertain the data (the coordinate value) on the movement of body surface on a real-time basis; (2) acceptance area break away monitoring; and (3) that evaluating the difference from the default. Besides, a program for an acquisition-correction was created to evaluate the accuracy and delay time using a statistical program.

2) The delay time in the acquisition-correction of the sensor data

The delay time in the acquisition-correction of the sensor data can be calculated by the formula (1).

$$\text{Minimum Delay Time}=((10\,\mu s+10\ ms)+(8\,\mu s\times 2))\times 3(*) \quad (1)$$

(10 μs: trigger pulse, 10 ms: time from end of echo to next trigger pulse, 8 μs: sonic burst, 2: loop, 3(*): limitation that serial processing makes coefficient multiplier delay for the correction of last axis)

3) Actual motion time and correction number in 1 cycle respiration of CBMP

The actual motion time and correction number in 1 cycle respiration of CBMP data can be calculated by the formula (2) and (3).

Sensoring and correcting 1 cycle time=(Motor motion time in 1 mm)+(Ultrasonic sensor measuring time)
=(392 ms)+(0.7 m/343 m/s)+10 μs)
=394 ms (excluding approximate 0.01 ms: data processing time) (2)

(392 ms: motor motion time in 1 mm, 0.7 m: maximum distance to the target (phantom bed), 343 m/s: sound velocity at 20°C in the air, 10 μs: trigger pulse)

Correction number in 1 cycle respiration=
(Target motion)/(Sensoring and correction 1 cycle time)
=(Lead time L: 60,000 ms÷21=2,857 ms, avg. 21/min)/(394 ms)
=7.3 correction (3)

(21: target average respiration cycle of rabbit in anesthesis, Laboratory animal medicine, Seoul Univ. p 183 Table 4~7, respiration cycle of rabbit: 45~55/min)

6. Animal experiment

Using the same methods described herein, the movement of body surface during respiration was acquired and corrected in a rabbit. Local anesthesia was performed to examine the body surface motion during cyclic respiration. The data was acquired for a total of 120 seconds. The data on the acquisition and correction was denoted on an acquisition/drive program in a sequential manner. The accuracy and delay time of data was assessed by using a plot of the change in the distance of coordinate versus time and a calculation formula for delay time (Fig. 4).

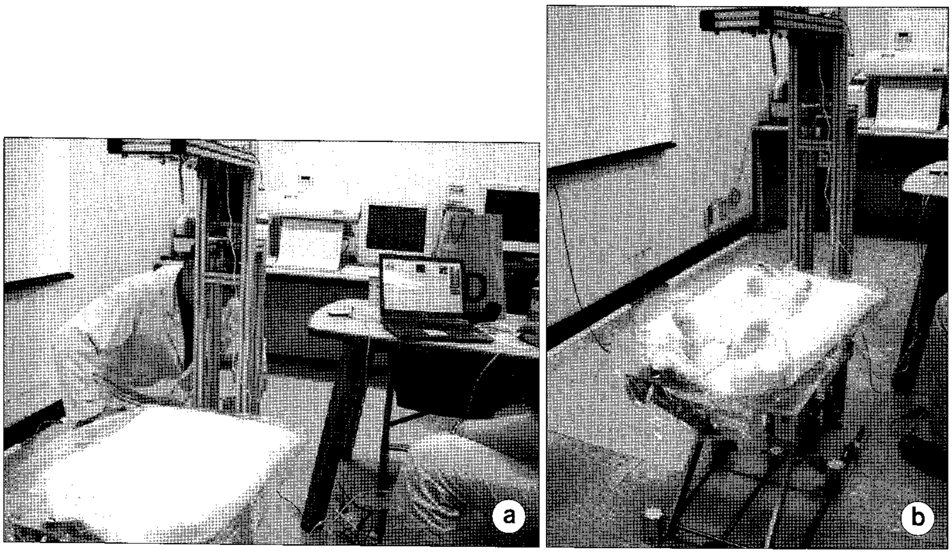

Fig. 4. It shows that respiration movements were acquired by using animals; (a) animal setup in moving phantom and acquisition-correction-analysis program, (b) animal setup in plate.

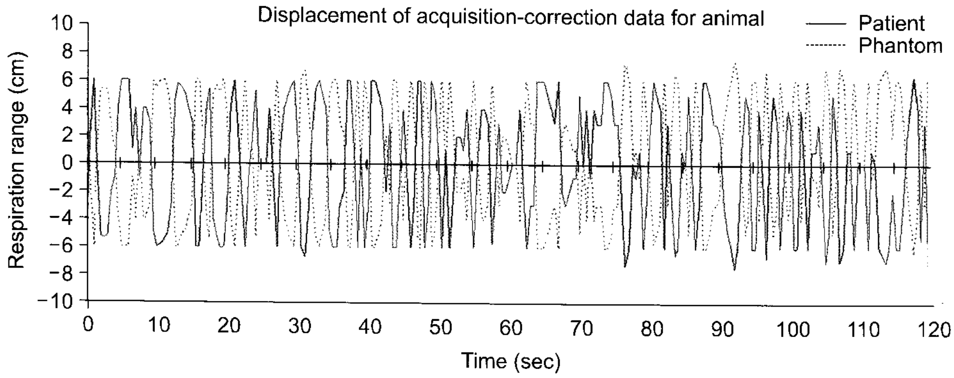

Fig. 5. The result of analyzing the acquisition-correction delay time for the three types of data values and about each value separately shows that the data values coincided with one another within 1% and that the acquisition-correction delay time was obtained real-time (2.34×10^{-4} sec). And the movement was the maximum movement was 6 mm in Z direction, in which the respiratory cycle was 2.9 seconds.

RESULTS

1. An acquisition-correction of data and its delay time

A program for an acquisition-correction of the sensor data was created, which included the following: (1) the part representing the coordinate value that makes it possible to ascertain the data (the coordinate value) on the movement of body surface on a real-time basis; (2) acceptance area break away monitoring; and (3) that evaluating the difference from the default. Besides, a program for an acquisition-correction was created to evaluate the accuracy and delay time using a statistical program.

The delay time in the acquisition-correction of the sensor data can be calculated by the formula (1). The delay time was 2.34×10^{-4} seconds.

2. Animal experiment

In a cat, regarding the movement of body surface during respiration, the data was acquired and then corrected using its reverse value. Then, to visualize the difference between the acquired and the corrected data, the displacement versus time was plotted and then summarized as a table. The acquisition and correction of data was done for a total of 120 seconds. According to the acquired data, the movement was the maximum movement was 6 mm in Z direction (anterior-posterior), in which the respiratory cycle was 2.9 seconds. To assess the accuracy between the acquired and the corrected data, the displacement versus time was plotted. This showed that there was a one-to-one relationship between the acquired and the corrected data, within a $\pm1\%$ range in Z direction (Fig. 5).

DISCUSSION AND CONCLUSION

The radiotherapy modulating the respiratory movement includes the respiration gating technique,[21-32] the arbitrary control of respiration,[8-11] breath-hold or active breathing control technique using a spirometer and tumor tracking system. In tumor tracking system, two representative methods are routinely done: (1) after fiducial landmark is placed onto the chest area, its image data is obtained by a CCD camera. By doing this, the movement of skin in the upper abdomen is visualized;[14-20] or (2) after the marker is inserted within the body, it is traced by a fluoroscope.[33-37]

Respiration gating radiotherapy techniques to manage respiratory induced tumor motion during radiation delivery include breath-holds, beam gating and real-time tumor tracking methods. Tumor tracking can be either MLC-based or couch-based.

To examine the movement of internal organs during respiration, a specialized device for the correction of respiration was developed by Tsukuba University in Japan in 1992. Since then, it has been widely used. In the USA in 1996, a device for the correction of respiration was developed by UCSF. In 1998, another device for the correction of respiration, ABC (active breathing control system) was developed by William Beaumont Hospital. Since then, it has been commercially available. Three-dimensional conformal radiotherapy was not effective in localizing the movement of tumor during the respiratory movement. By contrast, the radiotherapy modulating the respiratory movement is advantageous in controlling the respiration; minimizing the tumor movement; reducing the area for irradiation; and preventing the detrimental effect to adjacent tissue. Accordingly, many ongoing studies have been conducted.[38-40] However, ABC product has some disadvantages although it is used for respiration gating radiotherapy. The disadvantages include (1) the requirement of arbitrary gating of respiration, (2) the additional cost of purchasing high-priced equipment needed for the main operating system and (3) the absence of versatility. For this reason, ABC product is not appropriate for any hospitals that deal with multitude of patients since it will prolong the treatment time. Accordingly, the advanced radiotherapy regimen is needed to properly compensate the migration of target area following the movement of internal organs during respiration. So, breath-hold and gating techniques pose the disadvantage of increased treatment time. And MLC-based tracking is limited in resolution in one direction by the leaf width. Hence, it is imperative that the versatile system be developed in such a manner as to render the conventional radiotherapy equipment applicable to a clinical setting in Korea.

In the present study, we acquired the movement of body surface using both CBMP and sensor; and presented the new method that can optimize the bed using the reverse value of acquired data. In a phantom and an animal experiment, we analyzed the difference on the delay time between the acquisition and the correction data. To summarize, the results of the present study were as follows: (1) the data was consistent within a $\pm 1\%$ range and (2) on a real-time basis, the delay time for acquisition and correction was 2.34×10^{-4} seconds. These results showed that the new method of respiration gating radiotherapy described herein was clinically feasible.

The point of the present study is to make a real-time-based correction possible. Further studies are warranted to minimize the delay time for acquisition and correction.

To minimize the delay time for acquisition and correction, several methods can be considered. Firstly, in the current system, three coordinates move in a sequential manner according to a main MCU. This lengthens the delay time three times. Therefore, parallel processing is needed to make three coordinates move simultaneously in the presence of a MCU installed to each coordinate. Secondly, separated driving system is needed to control the acquisition-correction data in a differential manner. Finally, thirdly, the time for acquisition-correction should be shorter than the delay time of actually moving objects (hysteresis). Otherwise, the correction will cause the loss of acquired data. This covers the acquisition and correction of data and the time for a database.

Regarding the moving objects, the corrected value of acquired data will move the same beds simultaneously. However, the difficulty of free movement may occur due to the limitations in the making of rack and pinion gear. In the present study, the beds were made with a width of 5 mm. Accordingly, the small-sized beds are needed since the movement of less than 5 mm in gap will not be corrected. This is important in avoiding the further possible conflict with a linear accelerator. Besides, an ultrasonic sensor is another important factor in acquiring the same data. To overcome the inherent limitations of an ultrasonic sensor, other types of sensors including magnetic or ultrasonic sensors will be considered.

Hence, further studies are warranted to examine the clinical feasibility of the new method presented herein additionally on the dosimetric and clinical basis.

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CBMP (Couch Based Computer-Controlled Motion Phantom)와 초음파센서에 기반한 실시간 체표면 추적 시스템 개발: 타당성 연구

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호흡운동 조절 방사선치료 시 환자체표면 움직임을 추적하여 실시간 보정하고자 한다. 본 연구에서 사용한 시스템은 치료테이블에 기반을 둔 동 팬텀(CBMP, couch based computer-controlled motion phantom), 초음파 센서 및 제어, 구동, 분석 프로그램 등으로 구성하였다. 동물실험 결과 호흡주기는 2.9초이었고, 호흡진폭은 6 mm이었다. 실시간 체표면 추적시스템의 유용성 평가에 중요한 항목인 호흡운동 획득-보정간의 지연시간은 2.34×10^{-4} 초이어서 호흡운동 조절 방사선치료 시 사용할 수 있는 새로운 실시간 체표면 추적 기술의 임상적용에의 가능성을 확인할 수 있었다.

중심단어: 치료테이블에 기반한 동 팬텀(CBMP), 호흡운동 조절 방사선치료, 체표면 움직임, 센서, 방사선치료