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INTRODUCTION

Limb salvage surgery is the preferred treatment of choice for the primary bone cancer. Most limb salvage surgeries are successfully and safely performed with preoperative planning based on MR images and the assistance of intraoperative fluoroscopy. Recently, the navigation system has been introduced for intraoperative guidance. It can apply MRI and/or CT images to intraoperative visualization. This enables surgeons to intraoperatively identify the extent of tumors and to perform a more precise surgery. Especially, when a tumor is located adjacent to the joint, navigation-assisted surgery may be able to preserve the joint with a safe resection margin (1)(2).

Despite favorable attributes of navigation-assistance in decision of resection margin, somewhat cumbersome process and high cost may interfere with routine use of navigation in limb salvage surgery. To display the navigation tool correctly, preoperative patient-to-image registration is required. The registration and attachment of a reference marker on the patient's body is inconvenient and time-consuming, even though it is considered worthy of putting up with inconveniences.

Augmented reality (AR) navigation is in the limelight of minimal invasive surgery based on health information technology. AR is a term describing the overlay of information over real world imagery and in medical field, the information usually means computer generated imagery or radiologic data. AR is defined as a real-time direct or indirect view of a physical real-world

environment that has been enhanced/augmented by adding virtual computer-generated information to it. Despite its infancy, applications AR in medicine have been successful and promising. AR applications to orthopaedic surgery are not yet clinically available, but several research systems are being used to improve implant alignment (3). Variations on the application may include bone tumor resection.

We developed an AR-based navigation system which does not require segmentation for regions of interest, conventional registration and camera-tracker calibration. We focused on simplifying the navigation system for the purpose of bone tumor resection. Instead of segmentation, we used a graphic model which represents a virtual ruler as a reference for bone cutting. The proposed method does not use an external tracker such as an optical or magnetic tracker. Instead, we used a portable tablet PC to track the tools and display the information measured. In this study, we evaluated the accuracy of AR-based navigation assistance in resection of the bone tumor through a simulation of bone tumor in the pig femora.

MATERIALS AND METHODS

1) Development of AR-based navigation system

The AR-based navigation software is composed of three modules which are worked in the separated thread. The first module is for camera input/output and image processing. In this module, a camera image is captured by a frame grabber and then feature points are extracted from the image, which are used for a pose estimation algorithm. The estimated pose of reference markers are stored at the memory to share with other process modules. The second module is composed of 3D visualization functions by using VTK library. Proposed virtual template and additional interfaces are rendered in this thread. The last module includes the program interface such as button, message windows and background frame. To connect those separated modules, we used a design pattern and inter process communication method. All program modules are coded by C++ programming language and developed in Windows environment.

The proposed method does not need the external tracker such as optical or magnetic tracker. Instead of external tracker, we used a portable tablet PC embedded with camera. The AR based distance display system installed on the tablet PC to track the vision markers attached on tool and display the measured information in real-time. The tracking means finding a relationship between pose of camera and tool in real-time, and the pose contains position and orientation information (Figure 2.1). To track the tool, intrinsic

parameters and distortion parameters of the camera are necessary. Those camera parameters can be obtained from photogrammetric camera calibration method. In the experiment, we captured 30 chessboard images in every different position and those images were used for camera calibration by Zhang's calibration method (4). If the optical zoom and focus of the camera are fixed, the camera parameters are also constant and will still be available.

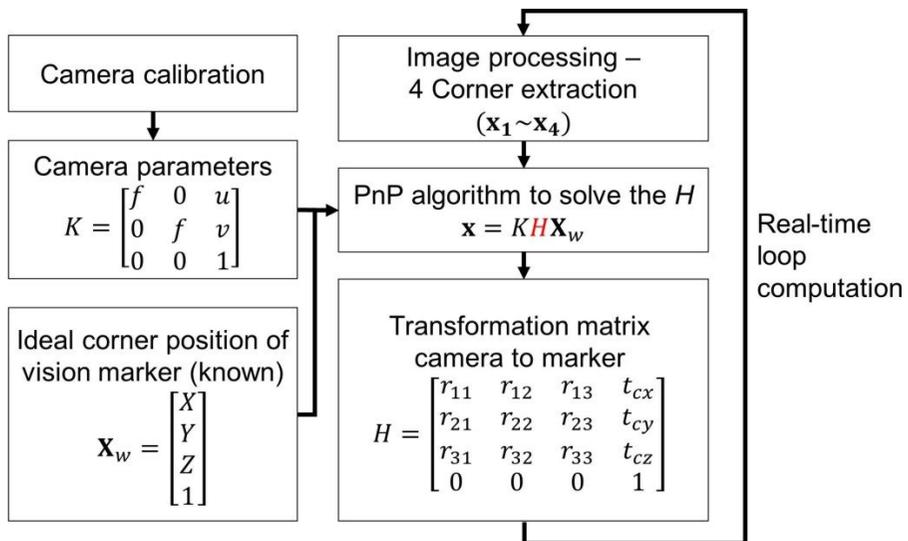


Figure 2.1. The pose estimation process of vision based tracker system. The computation of pose relationship between the camera center and vision marker (H) is the fundamental purpose.

The camera parameters gained from previous stage are used for the input parameters of the perspective n point (PnP) algorithm which computes a pose between the camera and vision marker. For the PnP algorithm, four corner points of the marker projected through the camera are needed. And the

extraction of corner point of the marker can be realized using the image processing in real-time. In this study, OpenCV library (5) was used for the image processing and the EPnP method (6) was applied to compute pose of camera and markers. In the experiment, two markers were used. The one was used as a reference of patient and the other was attached on the navigation tool. Two markers were tracked by the camera embedded in the tablet PC in real-time. Finally, the pose of the tool can be computed based on the reference marker of patient (Figure 2.2).

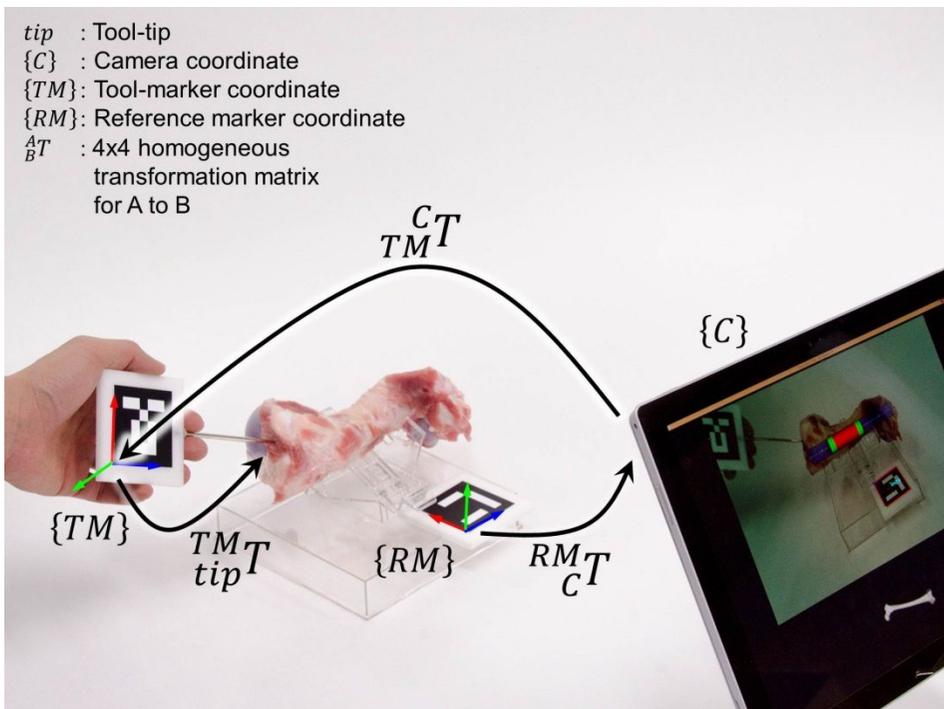


Figure 2.2. Two vision markers are traced by the camera of tablet PC. The purpose of a using the vision markers is tracking the tooltip based on the patient body. Reference marker should be fixed on the patient body. The relationship between reference marker and tool-tip (${}^{RM}_{tip} T$) can be calculated from the multiplication of three

transformation matrix: ${}^{RM}_{tip} T = {}^{RM}_C T {}^C_{TM} T {}^{TM}_{tip} T$

2) Evaluation of accuracy of the tracker system

An accuracy of the mono camera tracking system was evaluated by using a 3 axis computer numerical control robot (TinyCNC 6060C, Tinyrobot Inc., Korea) (figure 2.3). We set the camera in front of the robot and attached a reference marker at the robot arm. The robot was moved along the x, y and z axis in the camera field of view (FOV). The pose of reference marker was measured with 30 mm interval in the horizontal plane and 20 mm interval in vertical plane. A tracking error was represented as a Euclidian distance that is the difference between pose of robot and that on the computer.



Figure 2.3. Movement of the robot arm was tracked by the mono camera. The difference between the pose of robot arm and that on the computer is defined as tracking error.

3) Virtual template and registration

In the conventional navigation system, the segmentation and patient-to-image registration are necessary in order to display spatial information of tumor on the screen. However, for the bone tumor resection, we designed a simpler process using the virtual template. Instead of displaying the radiologic images, the cylinder-shaped virtual template was displayed on the patient body through AR. Virtual template contained the information on the longitudinal relationship between the normal tissue and the tumor, which was obtained from CT scan. The virtual template is composed of five stacked cylinders, the first and fifth cylinders represent a normal region. The third cylinder denotes extent of tumor, the second and fourth cylinder represent safety margin (figure 2.4).

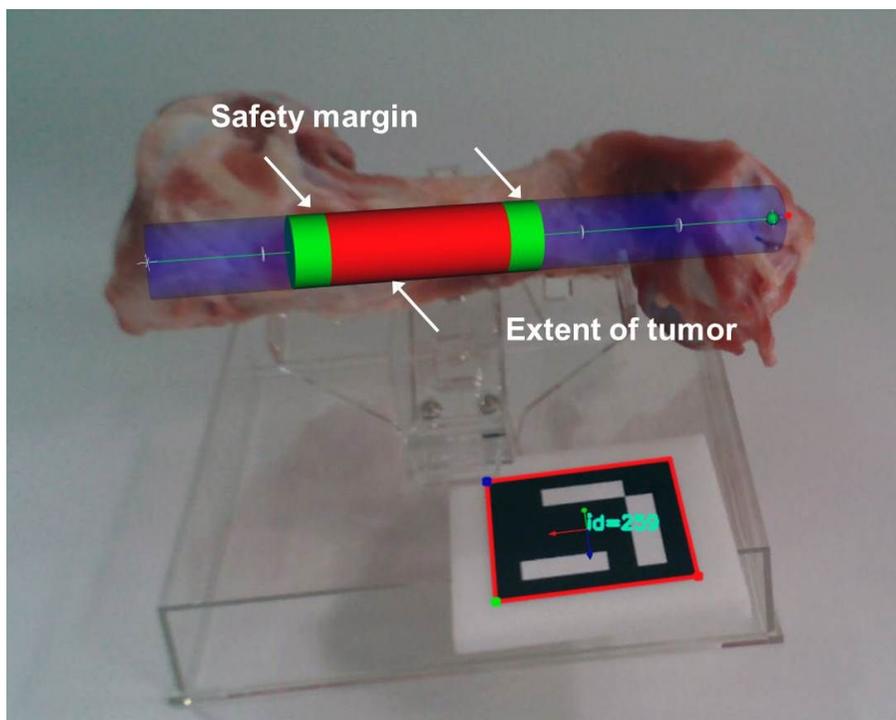


Figure 2.4. Cylinder-shaped virtual template overlaid on the computer screen

To accurately overlay the virtual template on the real bone, the simple registration process was necessary to match the both ends of virtual template and them of real bone. In the experiment, fluoroscopy was used for checking the both ends of the bone. This process with navigational probe under computer camera vision accomplished the registration (figure 2.5).

To visualize of the 3D object in our AR navigation, VTK library (7) was used. The navigation software was developed using C++ language and MFC library.



Figure 2.5. Paired-point registration with fluoroscopy under computer camera vision

5) Production of bone tumor model

In order to evaluate the efficacy and accuracy of AR-assisted bone tumor resection, we performed an animal study. This study was approved by institutional animal care and use committee of Seoul national university bundang hospital (No. BA1506-178/035-01). A sample power analysis showed that 39 femora for each group would be required at a significance level of 0.05 and 90% power, assuming a 2-millimeter difference in the resection error between the groups (mean [and standard deviation], 2 ± 3 millimeters for the AR group compared with 4 ± 3 millimeters for the conventional resection group). One hundred twenty three pig femora were employed in order to simulate bone tumor. A cortical window ($1 \times 2 \text{ cm}^2$) was made on the diaphysis and bone cement was inserted. CT scan was used to measure the length of bones and extent of cement inserted in all 123 femora (figure 2.6). Mean length of 123 pig femora was 190.7 millimeters and mean longitudinal extent of cement inserted was 57.5 millimeters.

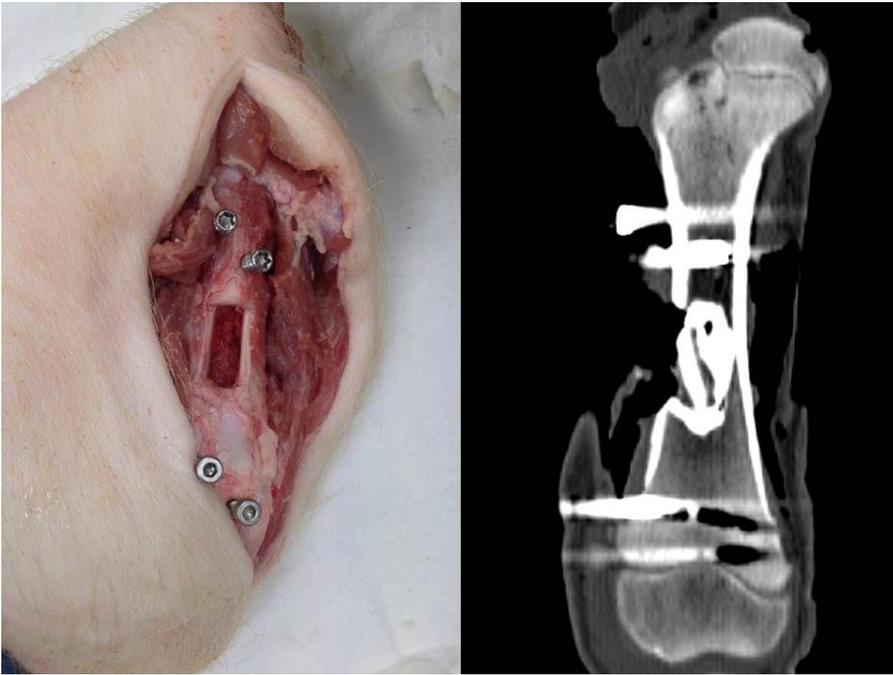


Figure 2.6. Bone tumor model using bone cement in the femur of a pig and CT scan

6) Comparison of AR-assisted resection and conventional resection

Tumor resection was simulated into 3 manners. One was AR-assisted resection by an expert orthopedic oncologist, another was AR-assisted resection by a junior orthopedic resident and the other was resection by conventional method. One hundred twenty three femora were assigned through 2:1 allocation to the AR-assisted resection group (AR group) or conventional resection group (conventional group) (figure 2.7). Bone tumor resection was simulated with 1-centimeter safety resection margin proximally and distally to bone cement. In conventional group, resection was performed by an expert orthopedic oncologist. Resection was planned based on CT

images and performed after measuring the distance from the edge of the condyle to the expected resection margin with a ruler as conventional manner. In AR group, resection for 41 bone tumor models was performed by the expert orthopedic oncologist and for remaining 41 by a junior orthopedic resident, respectively under AR-guidance. The distance from the edge of cement to the resection margin was evaluated by another orthopedic surgeon. 246 surgical margins of 123 femora were evaluated.

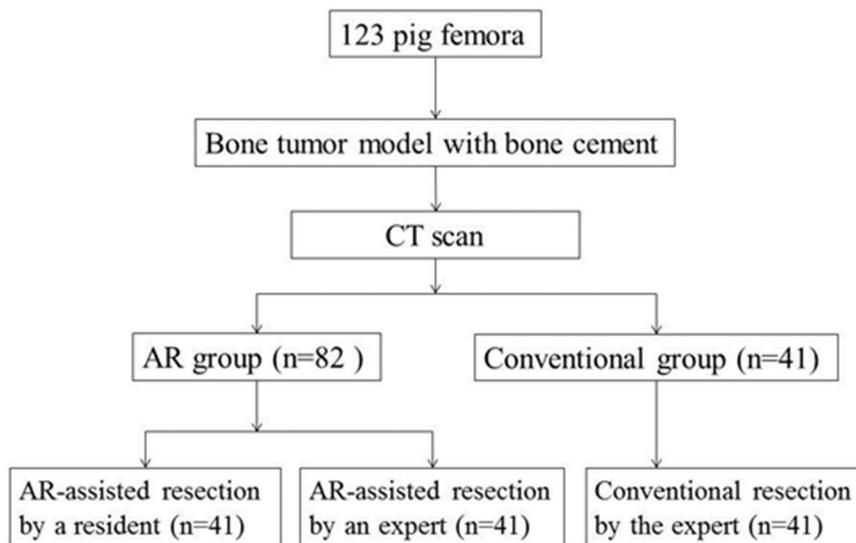


Figure 2.7. Allocation of pig femora

7) Outcome measurement

The difference between obtained surgical margin and planned surgical margin was regarded as error of resection and resections were classified into 4 grades:

Grade A, error ≤ 3 mm, grade; Grade B, $3 < \text{error} \leq 6$ mm; Grade C, $6 < \text{error} \leq 9$ mm; Grade D, error > 9 mm or tumor violation. Oneway ANOVA test was used for statistical comparison of the error of resection between the resection methods.

RESULTS

1) Accuracy of the tracker system

Tracking accuracy increased in the middle of FOV (field of view). The error of tracker system was less than 1 millimeter in following conditions: 1) the distance from the camera to the robot-arm was 25 to 36 centimeters; 2) the vertical and horizontal translation from the center of the view was less than 10 centimeters (figure 3.1).

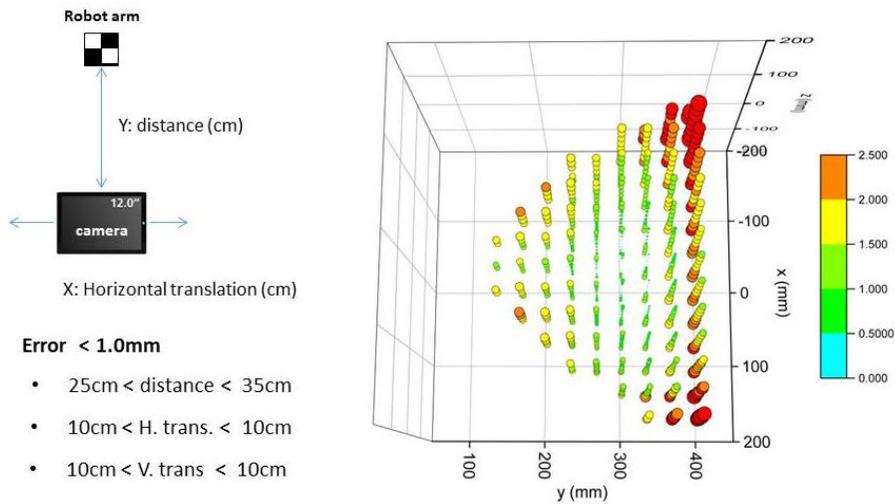


Figure 3.1. Tracking error was less than 1 millimeter when the distance from the object to camera was ranging 25 to 35 cm and translation in vertical and horizontal planes is less than 10 cm.

2) Comparison of AR-assisted resection and conventional resection

The mean error of 164 resections in 82 femora in the AR group was 1.71 mm (range, 0–6 mm: 1.76 mm in the expert resections and 1.65 mm in the resident resections $p = 0.58$). The mean error of 82 resections in 41 femora in the conventional group was 2.64 mm (range, 0–11 mm). A statistically significant difference was observed between AR-assisted and conventional resections by the expert ($p < 0.05$) (figure 3.2). By Levene's test, the distribution of errors of the three groups was significantly different ($p < 0.05$) (Figure 3.3). In the AR group, 148 resections were classified as grade A (72 expert resections, 76 resident resections) and 16 were classified as grade B (10 expert resections, 6 resident resections). No resections were classified as grades C or D in the AR group. In the conventional group, 58 resections were classified as grade A, 16 as grade B, 5 as grade C, and 3 as grade D. Although all resections were performed by an expert orthopedic oncologist in the conventional resection group, three resections had tumor violations or errors larger than 10 mm. The probabilities of a surgeon obtaining a 10-mm surgical margin with a 3-mm tolerance were 87.8% in AR-assisted resections by the expert, 92.7% in AR-assisted resections by the resident, and 70.7% in conventional resections by the expert (figure 3.4).

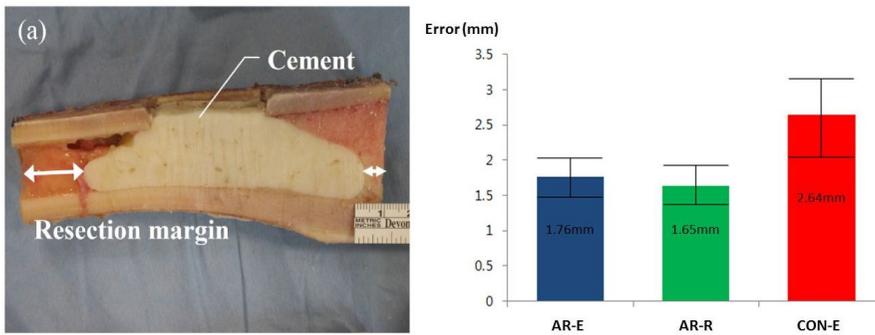


Figure 3.2. Measurement of error (a) The resection margin was evaluated. (b) The mean error of resection. A statistically significant difference was observed between AR-assisted and conventional resections. (AR-E: AR-assisted resection by an expert, AR-R: AR-assisted resection by a resident, CON-E: conventional resection)

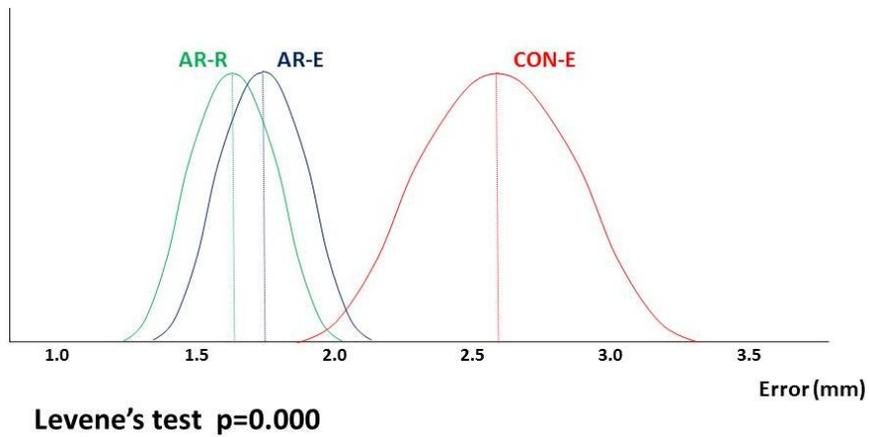


Figure 3.3. Distribution of the errors (AR-E: AR-assisted resection by an expert, AR-R: AR-assisted resection by a resident, CON-E: conventional resection)

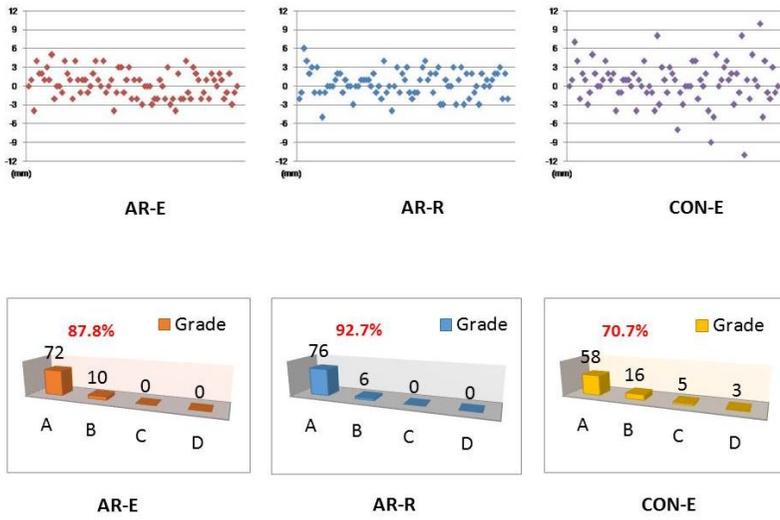


Figure 3.4. Distribution and grades of errors (AR-E: AR-assisted resection by an expert, AR-R: AR-assisted resection by a resident, CON-E: conventional resection)

DISCUSSION

Despite its infancy, attempts to apply augmented reality to medicine have been issued in some surgical fields including neurosurgery, otolaryngology and maxillofacial surgery. In this study, we developed an augmented reality (AR) navigation program for bone tumor resection, which runs on tablet PC. The results of experiment to evaluate the accuracy and usefulness of AR-guidance in bone tumor resection deemed to be satisfactory.

Augmented reality is a recent technology which combines computer-generated objects and text superimposed onto real images and video. The first appearance of AR dates back to the 1950s when Morton Heilig, a cinematographer, thought of cinema is an activity that would have the ability to draw the viewer into the onscreen activity by taking in all the senses in an effective manner. In 1962, Heilig built a prototype of his vision, which he described in 1955 in “The Cinema of the Future,” named Sensorama, which predated digital computing (8). Next, Ivan Sutherland invented the head mounted display in 1966. In 1968, Sutherland was the first one to create an augmented reality system using an optical see-through head-mounted display (9).

In some medical fields, mostly in surgeries, application of AR has been successful. In the preoperative planning, based on radiologic studies, most surgeons have a mental image of where the target lesion is and plan the route of exposure. In the AR environment, marking structures of interest on radiographic images that can be superimposed on live video camera images

allows a surgeon to simultaneously visualize the surgical site and the overlaid graphic images.

In orthopaedic oncologic field, the usefulness and accuracy of intraoperative navigation have been evaluated by many authors. Most of all, it proves its merit in the resection of pelvic ring tumor and metaphyseal tumors while preserving the adjacent joint [1]. An experimental study by Cartiaux et al (10) on the accuracy of tumour resection in the pelvis showed that the probability of an experienced surgeon obtaining a 1 cm surgical margin was only 52%. They attributed this inaccuracy to the complex 3D architecture of the pelvis, and suggested that the use of computer-or robot-assisted technology could improve this. We previously demonstrated that the advantages of navigation can be applied in limb salvage surgery and, in selected cases, it can maximize the accuracy of surgical resection and help to preserve the adjacent joint. However, comfort issues may limit prolonged use of navigation. Concerns may arise regarding fitting such ponderous instrument into an already crowded operating room environment. When a navigation system is employed in an operation of the long bone malignancy, what a surgeon wants to be informed from navigation is longitudinal relationships between the tumor, normal tissue and the adjacent joint. With the AR system in this study, what was shown is simple diagrammatic relationship of would-be-resected region and the normal bone, rather than the radiologic image itself which is displayed in the conventional navigation system. This concept made the software program be simple and require smaller memories than a conventional AR

program does. Because of simplification of the program, AR navigation environment could be embodied in a tablet PC.

Limitations of this study include simulation of tumor by bone cement. Malignancies in the bone usually have borders poorly defined because of aggressive growth and edema on the periphery. The determination of tumor border is hard in practice. On the other hand, in simulation of bone tumor with cement, the border of tumor is well-defined. However, the determination of tumor border is a concern of planning and this study was aimed to evaluate the accuracy in the performance of planned resection with AR-assistance. The determination of tumor border is not concern of this study. Another limitation is that the system needs the optimal distance between the object and system for the maximal accuracy. In the study for the evaluation of the accuracy of the tracker system, we found that tracking error was minimal when the distance from the object to camera was ranging 25 to 35 cm and translation in vertical and horizontal planes is less than 10 cm (figure 8). In experiment conditions, we could adjust the distance in optimal conditions. However, in practice, the conditions in operating room may not permit optimal distance for maximal accuracy. The other limitation is that the use of this program is confined to surgery for the long bone. In conventional navigation, the data provide by the system is the radiological images. It enables surgeon to identify the location and contour of the tumor intraoperatively. The navigation guidance is very helpful for surgeries for the pelvic bone malignancies as well as the long bone. The software of this study demonstrates only longitudinal relationship of the tumor to the bone, not the radiologic images. Therefore, it

can be used only in long bone surgery. For the pelvic malignancy, software specified for this region is required.

We developed an AR-based surgical navigation system for bone tumor surgery and evaluated the accuracy and usefulness by comparing with conventional method for bone tumor resection in bone tumor model. Based on the experimental results, the proposed method was more accurate than the conventional method. The most significant advantage of the proposed method is the convenience of the navigation.

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초 록

서론: 증강현실은 육안으로 보이는 현실에 컴퓨터가 제공하는 정보를 겹쳐서 보이게 하는 기술을 말한다. 수술용 증강현실 프로그램이 선보이고는 있지만 아직 정형외과 영역에서 적용된 보고는 없다. 본 연구에서는 모바일 기기를 기반으로 골종양 수술용 증강현실 어플리케이션을 개발하였고 돼지 대퇴골을 이용한 골종양 모델에 적용하여 그 정확성과 유용성을 평가하였다.

방법: 123개의 돼지 대퇴골에 창을 내고 골시멘트를 삽입하여 골종양 모델을 만들었다. CT를 촬영하여 골시멘트의 범위와 뼈 전장과의 관계를 확인하였다. 골종양의 절제는 3가지 방법으로 시행되었는데, 골종양 전문가와 정형외과 전공의가 각각 개발된 증강현실 어플리케이션을 이용하여 절제하였고, 나머지는 골종양 전문가가 일반적인 골종양 수술 방법을 이용하여 절제하였다. 통계는 일방향 ANOVA 분석을 이용하여 각군간의 절제 오차를 비교하였다.

결과: 계획된 절제범위와 실제 절제범위를 측정한 결과 증강현실을 이용한 군과 일반적 골종양 수술 방법군 간에는 통계적으로 유의한 차이가 있었다($p < 0.05$). 증강현실을 이용한 절제에서는 평균 오차가 1.71 mm(범위, 0-6 mm)이었고, 일반적인 골종양 수술 방법군의 평균 오차는 2.64 mm(범위, 0-

11 mm)이었다. 또한, 10mm의 절제연을 계획하고 수술할 때 3mm 이하의 오차를 갖을 확률이 증강현실군에서는 87.8%(골종양 전문가)와 92.7%(정형외과 전공의)이었고, 일반적 골종양 수술 방법군에서는 72.0%이었다.

결론: 골종양 수술용 증강현실 프로그램은 안전하고 정확한 악성 골종양 절제에 도움이 될 것으로 사료된다.

주요어: 골종양, 항법장치, 증강현실, 어플리케이션, 모바일 기기

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