

## A novel 3D guidance system using augmented reality for percutaneous vertebroplasty

### Technical note

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Augmented reality (AR) is an imaging technology by which virtual objects are overlaid onto images of real objects captured in real time by a tracking camera. This study aimed to introduce a novel AR guidance system called virtual protractor with augmented reality (VIPAR) to visualize a needle trajectory in 3D space during percutaneous vertebroplasty (PVP).

The AR system used for this study comprised a head-mount display (HMD) with a tracking camera and a marker sheet. An augmented scene was created by overlaying the preoperatively generated needle trajectory path onto a marker detected on the patient using AR software, thereby providing the surgeon with augmented views in real time through the HMD. The accuracy of the system was evaluated by using a computer-generated simulation model in a spine phantom and also evaluated clinically in 5 patients.

In the 40 spine phantom trials, the error of the insertion angle (EIA), defined as the difference between the attempted angle and the insertion angle, was evaluated using 3D CT scanning. Computed tomography analysis of the 40 spine phantom trials showed that the EIA in the axial plane significantly improved when VIPAR was used compared with when it was not used ( $0.96^\circ \pm 0.61^\circ$  vs  $4.34^\circ \pm 2.36^\circ$ , respectively). The same held true for EIA in the sagittal plane ( $0.61^\circ \pm 0.70^\circ$  vs  $2.55^\circ \pm 1.93^\circ$ , respectively).

In the clinical evaluation of the AR system, 5 patients with osteoporotic vertebral fractures underwent VIPAR-guided PVP from October 2011 to May 2012. The postoperative EIA was evaluated using CT. The clinical results of the 5 patients showed that the EIA in all 10 needle insertions was  $2.09^\circ \pm 1.3^\circ$  in the axial plane and  $1.98^\circ \pm 1.8^\circ$  in the sagittal plane. There was no pedicle breach or leakage of polymethylmethacrylate.

VIPAR was successfully used to assist in needle insertion during PVP by providing the surgeon with an ideal insertion point and needle trajectory through the HMD. The findings indicate that AR guidance technology can become a useful assistive device during spine surgeries requiring percutaneous procedures.

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**KEY WORDS** • augmented reality • computer-assisted surgery •  
percutaneous spinal approach • percutaneous vertebroplasty • technique

**A**UGMENTED reality (AR) is a technology that can enhance visual perception through rendered information generated by a computer. Various applications using AR have rapidly developed in many scientific and commercial fields in recent decades. By overlaying computer-generated virtual objects on the captured images of real objects, AR systems can intuitively provide

users a wealth of useful information. Recently, several experimental trials of medical AR systems have been reported in the field of spinal surgery. Bichlmeier and colleagues have proposed the use of AR for pedicle screw placement and reported superior accuracy of an AR navigation system with a head mount display (HMD) in experimental spine phantoms.<sup>4</sup> The authors of MRI-guided spinal biopsy studies using an AR system<sup>8,10,25</sup> and AR-assisted thoracoscopy studies have also reported satisfactory accuracy using experimental models.<sup>5,23</sup>

This article contains some figures that are displayed in color online but in black-and-white in the print edition.

*Abbreviations used in this paper:* AR = augmented reality; CAS = computer-assisted surgery; EIA = error of the insertion angle; HMD = head mount display; PMMA = polymethylmethacrylate; PVP = percutaneous vertebroplasty procedure; VIPAR = virtual protractor with augmented reality.

## Novel augmented reality-assisted percutaneous vertebroplasty

Recently, minimally invasive surgery techniques have become widespread in spinal surgery, and the frequency of using a percutaneous approach to access the spine has increased.<sup>2,7,9,11,15</sup> Vertebroplasty for osteoporotic vertebral fractures is a typical surgery requiring a percutaneous transpedicular approach. This procedure is commonly performed under fluoroscopy guidance and is recognized as relatively easy and safe, but inadequate needle placement has the potential to cause neurovascular injury or cement leakage.<sup>6,7,12,14,21,27</sup> Computed tomography-based navigation or O-arm imaging has been reported to improve the accuracy of needle placement<sup>3,13,18</sup>; however, the use of these systems is time consuming and the systems themselves are expensive.

We developed a novel AR guidance technique to visualize the needle insertion point on the patient's skin and the 3D trajectory path using an HMD without the time-consuming registration method generally required by CT-based navigation systems. This new technique, known as virtual protractor with augmented reality (VIPAR), is affordable because it requires only commodity hardware and inexpensive software such as a web camera and a low-cost HMD. The purpose of this study was to validate this novel guidance technique using a spine phantom and introduce its clinical application.

### Methods

Institutional review board approval was acquired from Eniwa Hospital.

#### Basic VIPAR Technique

##### Preoperative Preparation.

**First Step: Determination of Needle Trajectory.** The needle trajectory was analyzed using 3D CT scans. In the present study, 3 spinal levels with fractured vertebrae were scanned with a thickness of 0.5 mm and a pixel spacing of 0.35 mm (Aquilion 64, Toshiba Medical Systems Corp.). The ideal skin insertion point, 3D needle trajectory, and ideal insertion point on the bony surface were analyzed on the basis of CT data obtained using a previously developed 3D-VG TIPS viewer<sup>1</sup> (3D visual guidance technique for inserting pedicle screws; ZedView VEGA, Robert Reid—LEXI [Fig. 1]). A needle trajectory model was automatically generated as a 3D object.

**Second Step: AR System Settings.** A high-resolution web camera (C905 m, Logicoool) was attached to the see-through HMD system (Moverio, Epson). The HMD was connected to a laptop computer using wireless LAN and provided the surgeon a mirror image in real time on a computer monitor. Augmented-reality software was used to determine the orientation of the detected marker with respect to the video image captured by the HMD camera. It was then able to create an augmented scene by overlaying a 3D needle trajectory image on to the detected marker (Fig. 2). In the present study, the ARToolKit software library was used to achieve augmented vision.

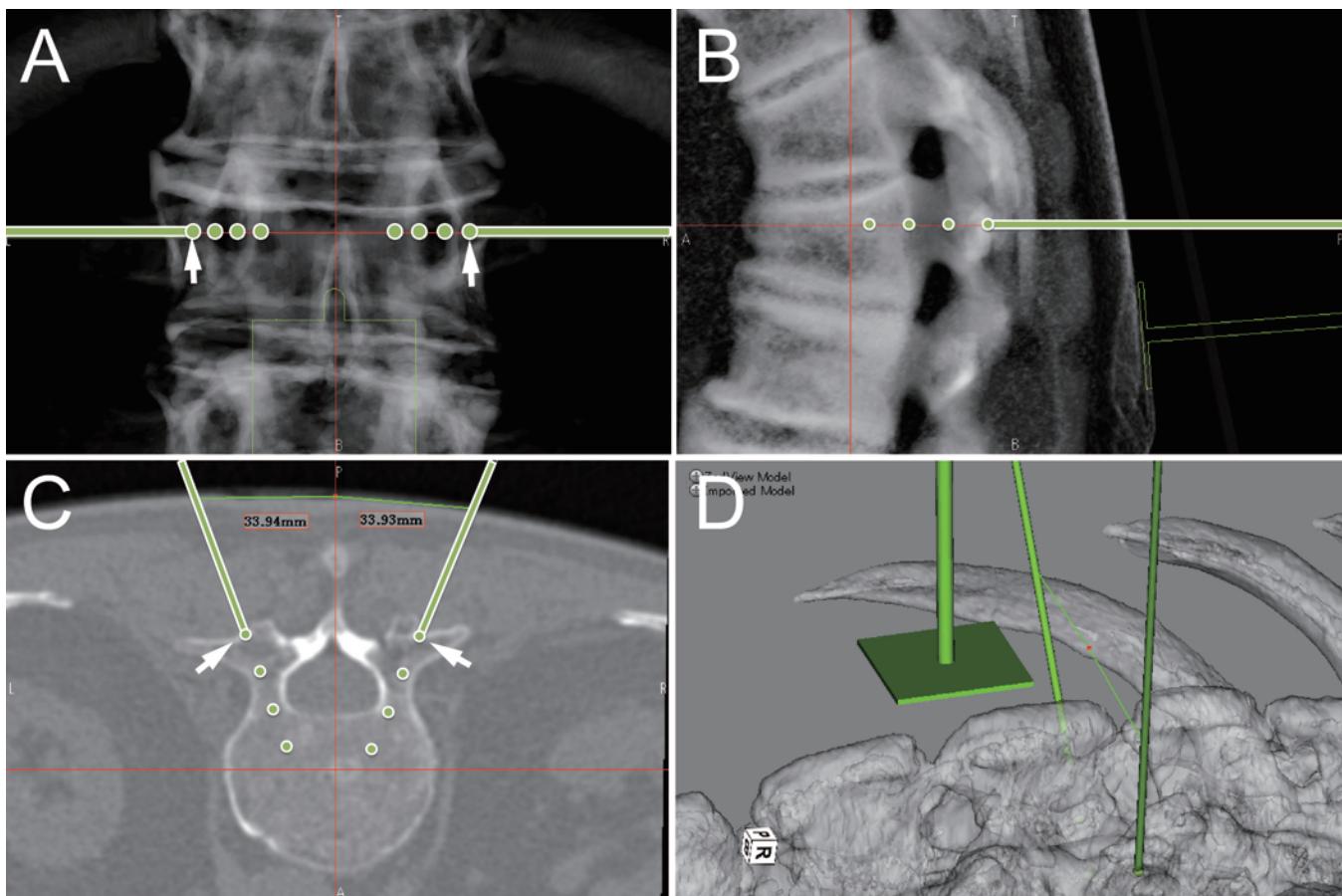
**Intraoperative Guidance Using VIPAR.** First, the 3D position of the fractured vertebral body was adjusted using fluoroscopy. The sagittal axis of the vertebra that was

analyzed before surgery was adjusted in a direction vertical to the area under fluoroscopic guidance (Fig. 3A). An accurate lateral view of the vertebra is required because the sagittal axis was designed to be completely parallel to the needle trajectory. If the vertebral body exhibits lateral wedging due to an asymmetrical fracture, its coronal inclination must be adjusted by referencing the outline of the bilateral pedicles. Vertebral rotation also should be adjusted; however, significant rotation is a contraindication for VIPAR. Ultimately, outlines of the bilateral pedicles were identified on posteroanterior fluoroscopy and the coronal inclination was adjusted. Next, a marker sheet for VIPAR was placed on the skin. The axial plane, including the bilateral needle pathway, was perpendicular to the ground and ran through the center of the bilateral pedicles (Fig. 3B). The line that passed along the center of both pedicles was drawn on the skin, and needle insertion points were marked on both sides after measuring the distance from the midcentral line according to the preoperative analysis (Fig. 3C and D). A sterile marker sheet was placed just caudal to the insertion point on the skin. The operator wore the HMD and confirmed that the entry point marked on the skin exactly overlapped with the entry point on the 3D object.

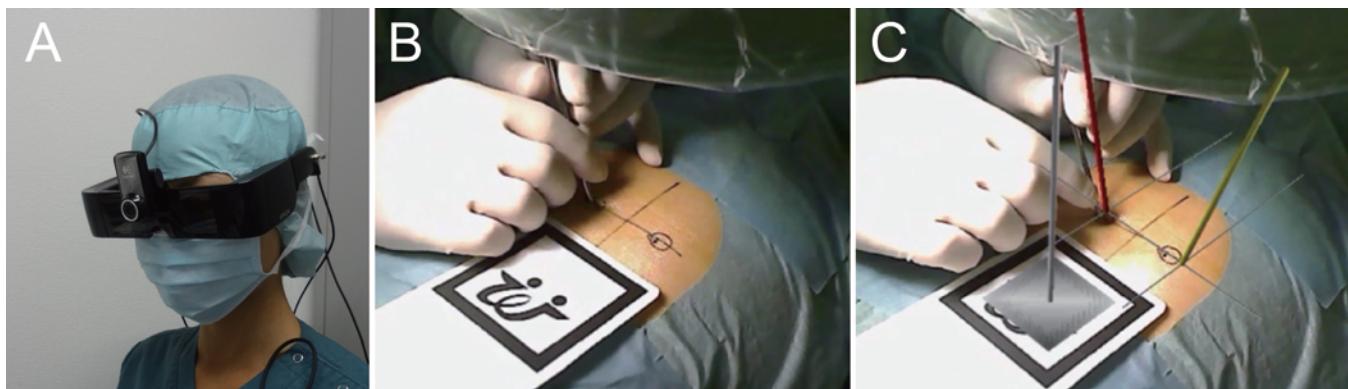
Without fluoroscopic guidance, the needle was then inserted at the marked insertion point and advanced parallel to the overlaid guideline on the augmented view until its tip reached the bony surface (Fig. 3D). The accuracy of the position of the needle tip was then confirmed by referencing the outline of the pedicle using posteroanterior fluoroscopy (Fig. 3B). This conventional confirmation process may be omitted as long as the position of the inserted needle and that of the augmented guideline are identical; however, we strongly recommend performing the confirmation step carefully under fluoroscopic guidance to ensure patient safety. The needle was advanced into the vertebral body through the pedicle without fluoroscopic guidance. During this procedure, the needle must remain parallel to the augmented guideline. The actual needle trajectory and augmented guideline were confirmed from positions caudal, lateral, or directly behind the needle axis by movement of the operator's head. Ultimately, the depth of the needle tip was confirmed by lateral fluoroscopy.

#### VIPAR Validation Using Spine Phantoms and Clinical Trials

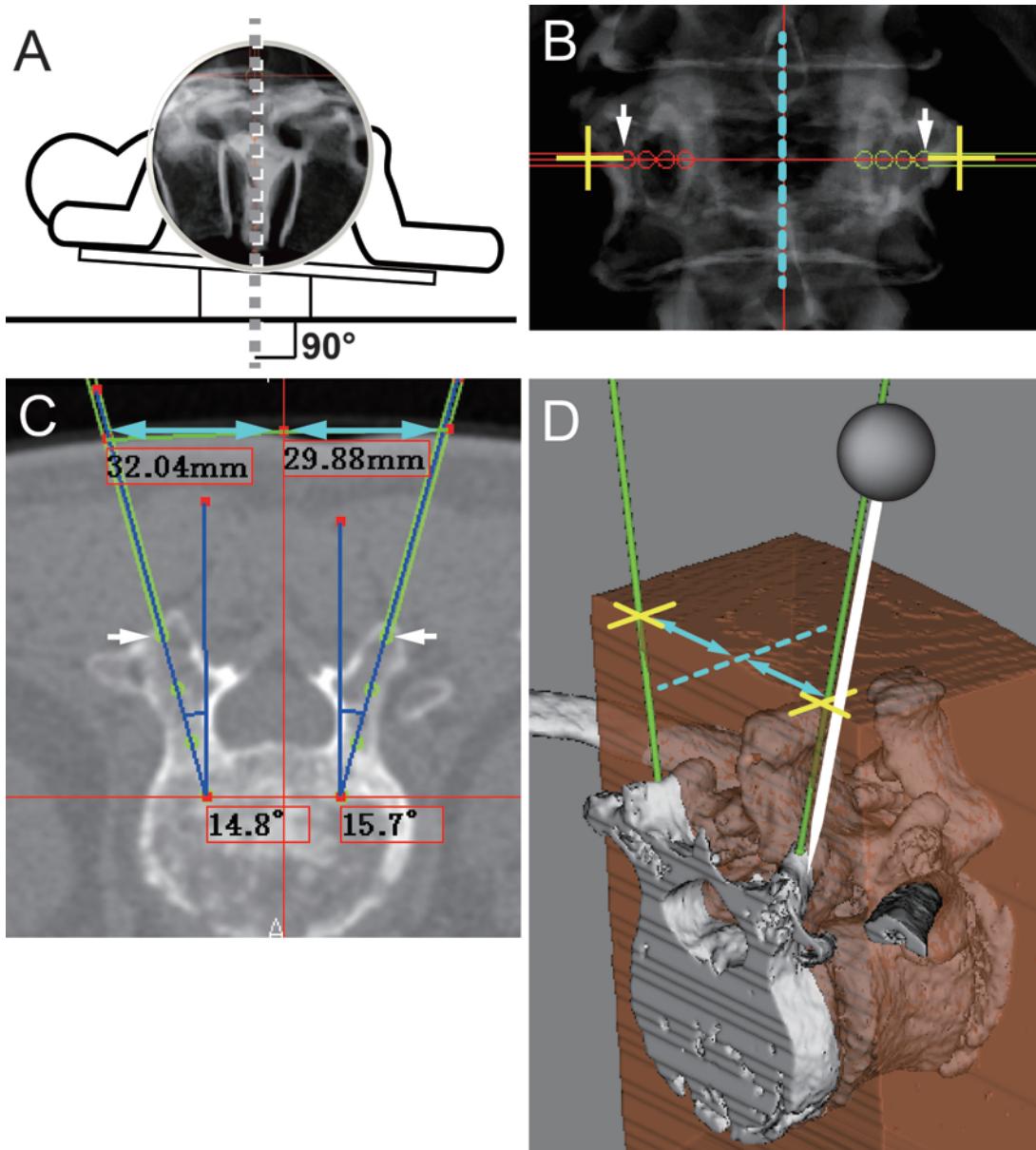
**Validation 1: Evaluation Using Spine Phantoms.** The accuracy of AR-assisted needle insertion was evaluated using 2 different spine phantom simulation models. For the percutaneous vertebroplasty procedure (PVP), 2 different needle trajectories were commonly used. The standard trajectory was through the transpedicular pathway similar to a thoracic pedicle screw. It was tilted 10°–15° in the axial plane and parallel to the vertebral axis in the sagittal plane. Model A was designed to mimic this standard trajectory using a simulated needle trajectory tilted 15° in the axial plane and 0° in the sagittal plane. In the upper or middle thoracic levels, the needle was inserted from the cephalolateral portion of the pedicle directly



**FIG. 1.** Preoperative preparation of the needle trajectory model for the VIPAR-guided procedure. **A:** Simulative fluoroscopic image generated from CT data obtained using the originally developed software. Arrows indicate the ideal insertion point on the bony surface from the posteroanterior view. **B:** The ideal needle trajectory is indicated on the simulative lateral fluoroscopic image. **C:** The ideal needle trajectory in the axial plane is shown. The distance of the insertion point from the midcentral line on the skin is calculated automatically. Arrows indicate the insertion point on the bony surface. **D:** A generated 3D model of the needle trajectory and marker. These objects are transferred to the AR software.



**FIG. 2.** Augmented view provided by a video see-through HMD. **A:** The HMD with a camera. The captured view is sent to a computer and a generated augmented view is returned to the HMD. The surgeon can see the real object and augmented scene simultaneously through the video see-through display. **B:** Captured raw image of the operative scene by the camera mounted on the HMD. The white sheet with black square is the marker sheet. **C:** Augmented view that the operator actually sees through the HMD. The software determines the orientation of the detected marker and creates the augmented scene by overlaying generated 3D objects. The gray square with perpendicular line is matched with the coordinate of the marker sheet. The augmented oblique red line and yellow-green line indicate the ideal insertion point and needle trajectory. The surgeon can easily check the trajectory from different angles by changing his or her head position.



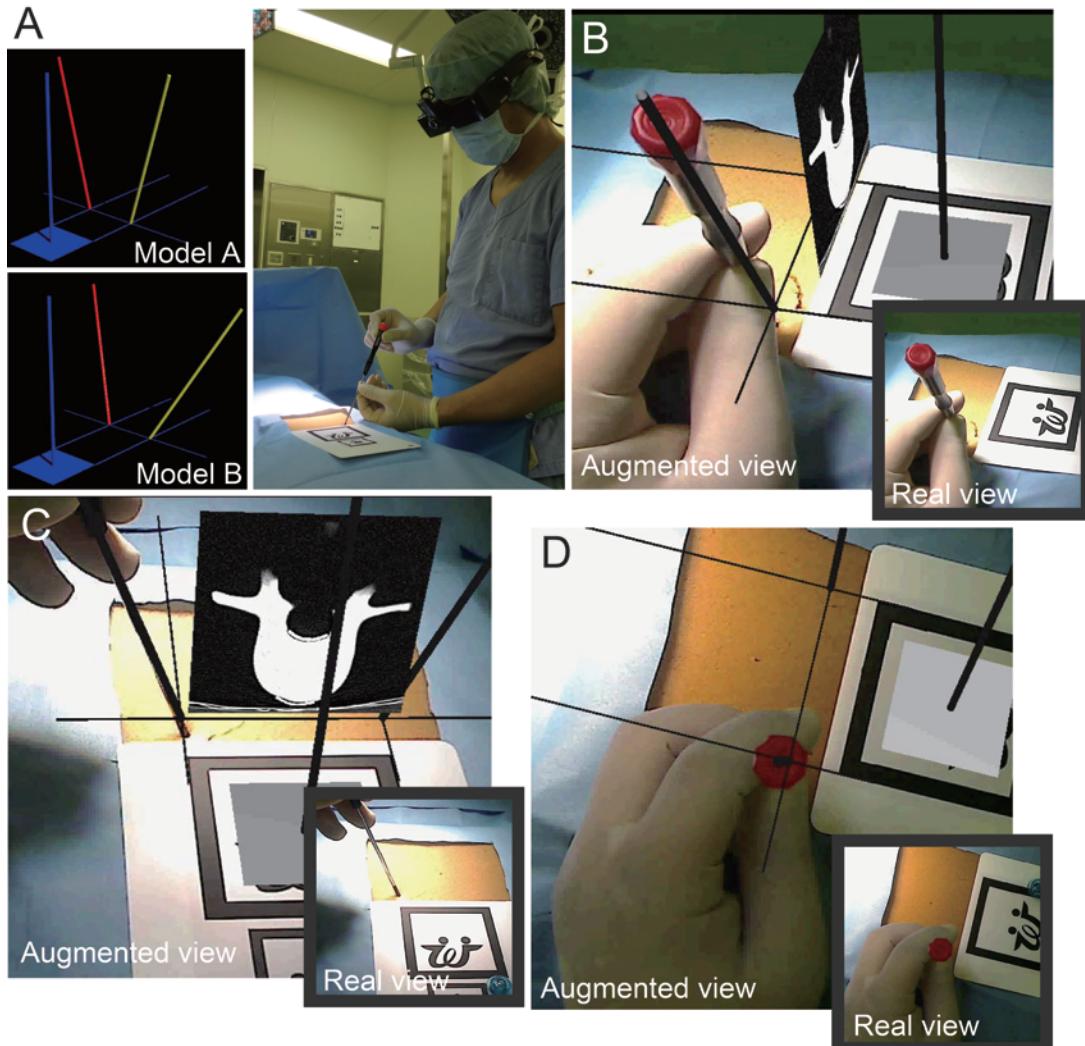
**Fig. 3.** Operative guidance method using VIPAR. **A:** Intended needle path is adjusted vertical to the ground under lateral fluoroscopic guidance. **B and C:** Insertion level is confirmed with a posteroanterior view and the insertion point (yellow crosses) is marked on the skin. Blue dotted line is the midcentral line. The blue arrows indicate the distance from the midcentral line to the insertion point. The white arrows indicate the ideal insertion point on the bony surface. **D:** Schematic image of needle insertion. The needle is inserted from the marked insertion point (yellow crosses) parallel with the augmented guideline displayed on the HMD. After confirming that the position of the needle tip matches the ideal insertion point, the needle is advanced into the vertebra.

to the vertebral body because of the smaller diameter of the pedicle. The needle trajectory was more oblique in the axial plane and tilted cephalad in the sagittal plane. Therefore, Model B was designed to mimic this oblique trajectory with a simulated trajectory tilted 25° in the axial plane and 20° in the sagittal plane (Fig. 4A).

The augmented view provided by VIPAR during needle insertion in the spine phantom is illustrated in Fig. 4B–D. Bilateral entry points were indicated on the phantom surface, and the 3D trajectory of the needle and axial CT scan were augmented on the captured image in real

time. Using this system, the operator can confirm with ease the ideal trajectory from any view angle as per requirement.

Needles were inserted 40 times with or without the aid of the VIPAR system by 2 operators. The spine phantom was scanned using a CT scanner. The accuracy of the VIPAR system was evaluated by the angle of the needle path on the preoperative planning images and postoperative CT scans. The error of the insertion angle (EIA) was defined as the absolute value of the difference between the attempted angle and the actual insertion angle (Fig.



**Fig. 4.** Simulative models and AR-assisted needle insertion using the spine phantom. **A:** Two different models are used. In Model A, the needle trajectory tilts 15° in the axial plane and 0° in the sagittal plane. In Model B, the trajectory tilts 25° in the axial plane and 20° in the sagittal plane. These models are overlaid on the captured image and an augmented view is provided to the surgeon through the HMD. **B:** A captured view and augmented view from the posterolateral direction. The ideal needle trajectory and insertion point are indicated in the augmented view. The operator can check the direction of the needle intuitively. **C:** A caudal view. The operator can confirm the ideal trajectory from any angle as required. **D:** View from straight behind the needle axis. Both the insertion point and needle trajectory are completely matched with the preoperative plan.

5)—that is, if the preoperative attempted angle was 15° and the inserted angle was 13°, the EIA was 2°.

**Validation 2: Evaluation of 5 Clinical Cases.** Five consecutive patients in whom osteoporotic vertebral fractures were diagnosed between October 2011 and May 2012 were enrolled in the study. Their average age at surgery was 75.2 years (range 67–82 years), and their average bone mineral density was  $0.594 \pm 0.071 \text{ mg/cm}^2$  (T-score  $-1.94 \pm 0.47$ ). The fractured spinal level was T-12 in 2 patients, L-1 in 2, and L-3 in 1. The average duration of preoperative conservative treatment was 2.4 months, and all 5 patients were diagnosed with nonunion based on CT and MRI findings (Table 1). Computed tomography was used to examine 3 spinal levels with fractured vertebrae, with a thickness of 0.5 mm. This CT scan format is conventionally used for making reconstruction images, and

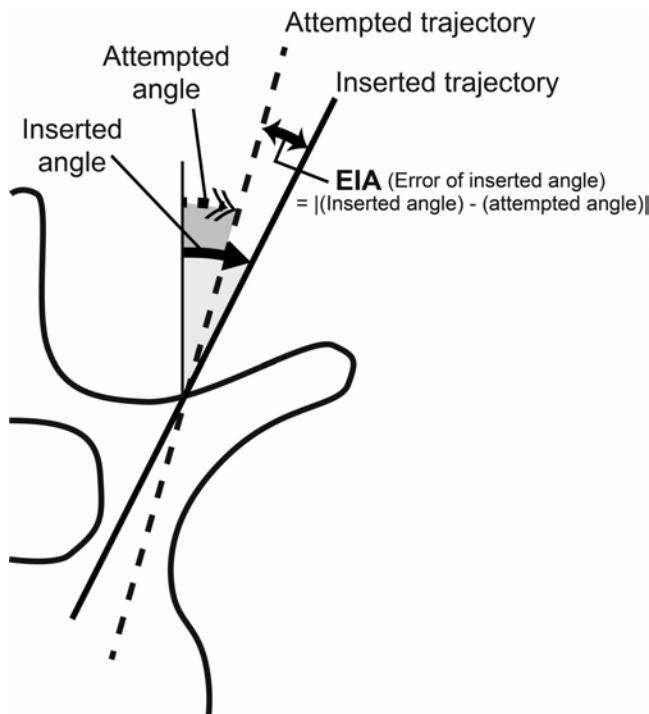
it did not require additional or special radiation exposure for preoperative planning using VIPAR.

## Results

### Evaluation Using Spine Phantoms

The results showed that the EIAs in the axial plane in both models were significantly improved for both operators in the VIPAR group compared with those in the group in which VIPAR guidance was not used (non-VIPAR group) (Table 2). In Model A, the mean axial-plane EIAs were 4.18° and 0.96° and the mean sagittal-plane EIAs were 1.75° and 0.47° in the non-VIPAR and VIPAR groups, respectively. Both sagittal- and axial-plane EIAs were significantly smaller in the VIPAR group than in the non-VIPAR group. Two-dimensional distribution of the

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**Fig. 5.** Schematic illustration of the error of insertion angle (EIA). The EIA is defined as the absolute value of the difference between the attempted angle and the actual angle of insertion. The attempted angle is the angle between the vertebral axis and attempted trajectory and is measured using preoperative workups. The insertion angle is measured on postoperative CT scans.

needle angle is shown in Fig. 6. The distribution pattern was smaller in the VIPAR group than in the non-VIPAR group, and all needles in the VIPAR group were placed inside of a  $2.5^\circ$  circle. In Model B, the mean axial-plane EIAs were  $4.51^\circ$  and  $0.96^\circ$  and the mean sagittal-plane EIAs were  $2.97^\circ$  and  $1.09^\circ$  in the non-VIPAR and VIPAR groups, respectively, indicating a similar result as that of Model A. The sagittal-plane EIAs in Model B were significantly larger than those in Model A, and the distribution pattern spread widely in the sagittal plane in Model B. This trend was more obvious in the non-VIPAR group than in the VIPAR group (Fig. 6). The overall average axial-plane EIA showed a significant improvement, from  $4.34^\circ \pm 2.36^\circ$  in the non-VIPAR group to  $0.96^\circ \pm 0.61^\circ$  in the VIPAR group, whereas the overall average sagittal-

plane EIA showed a significant improvement from  $2.55^\circ \pm 1.93^\circ$  in the non-VIPAR group to  $0.61^\circ \pm 0.70^\circ$  in the VIPAR group.

### Results of the 5 Clinical Cases

Percutaneous vertebroplasty procedure with polymethylmethacrylate (PMMA) was performed under VIPAR and fluoroscopic guidance. The average duration of surgery was 49.2 minutes, and the average time for bilateral needle insertion using VIPAR was 14.8 minutes. The average duration of radiation exposure was 253 seconds during surgery, whereas that required to complete bilateral VIPAR procedures was 112 seconds (Table 3).

The insertion route of the approaching needle was analyzed using postoperative 3D CT. The EIA for all 10 needle insertions was  $2.09^\circ \pm 1.3^\circ$  (range  $0.4^\circ$ – $3.9^\circ$ ) in the axial plane and  $1.98^\circ \pm 1.8^\circ$  (range  $0^\circ$ – $4.4^\circ$ ) in the sagittal plane (Table 4). There was no pedicle breach or PMMA leakage. Preoperative back pain improved in all 5 cases, and the visual analog scale score improved from 86.2 to 42.0 at 2 months after surgery.

### Illustrative Case

A 68-year-old woman was diagnosed with an osteoporotic vertebral fracture at the T-12 level. She was injured during a fall and suffered severe back pain for 3 months. An intervertebral cleft was clearly visible on radiographs and CT scans obtained during her initial visit to our hospital. Percutaneous vertebroplasty (Kyphon Balloon Kyphoplasty [Medtronic]), with PMMA, was performed under fluoroscopic guidance. The optimal needle insertion point and the needle trajectory were analyzed before surgery. The needle was inserted while visualizing the ideal trajectory on the augmented view through the HMD monitor (Video 1).

**VIDEO 1.** Intraoperative guidance using VIPAR. A marker sheet is placed just caudal to the insertion point. The captured view of the operative field is sent to a computer, and a generated augmented view is returned to the HMD. The 3D object of the marker (gray line) and needle trajectory (red and yellow lines) is overlaid onto the real objects captured by a camera. The needle is inserted parallel to the augmented trajectory line displayed on the HMD. The surgeon can easily check the trajectory from different angles by changing head position. Copyright Yuichiro Abe. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

**TABLE 1: Demographic data and clinical results of each patient\***

Case No.	Age (yrs), Sex	Spinal Level	BMD (mg/cm <sup>2</sup> )	VAS Score (mm)	
				Preop	2 Mos Postop
1	81, M	L-1	0.648	76	32
2	67, M	L-1	0.660	87	41
3	82, F	T-12	0.626	98	52
4	78, F	L-3	0.525	78	38
5	68, F	T-12	0.510	92	47
mean $\pm$ SD	75.2		0.594 $\pm$ 0.071	86.2 $\pm$ 9.3	42.0 $\pm$ 7.8

\* BMD = bone mineral density; VAS = visual analog scale.

TABLE 2: Error in the insertion angles in both simulation models ( $\pm$  SD)

Simulation Model	Axial Plane (°)		Sagittal Plane (°)	
	w/o VIPAR	w/ VIPAR	w/o VIPAR	w/ VIPAR
<b>Model A</b>				
Operator 1	4.10 $\pm$ 2.05	1.05 $\pm$ 0.84*	1.87 $\pm$ 1.47	0.41 $\pm$ 0.42†
Operator 2	4.25 $\pm$ 3.24	0.86 $\pm$ 0.42*	1.62 $\pm$ 1.17	0.52 $\pm$ 0.46
total	4.18 $\pm$ 2.64	0.96 $\pm$ 0.65‡	1.75 $\pm$ 1.30	0.47 $\pm$ 0.43§
<b>Model B</b>				
Operator 1	4.02 $\pm$ 2.88	1.22 $\pm$ 0.58*	3.27 $\pm$ 2.10	1.16 $\pm$ 0.92†
Operator 2	4.99 $\pm$ 2.14	0.70 $\pm$ 0.49*	2.67 $\pm$ 2.50	1.01 $\pm$ 0.65
total	4.51 $\pm$ 2.52	0.96 $\pm$ 0.59‡	2.97 $\pm$ 2.27	1.09 $\pm$ 0.78‡

\* p < 0.01; EIA for both groups (without VIPAR vs with VIPAR; n = 10) and both operators were analyzed with Tukey test.

† p < 0.05; EIA for both groups (without VIPAR vs with VIPAR; n = 10) and both operators were analyzed with Tukey test.

‡ p < 0.01; EIA for both groups (without VIPAR vs with VIPAR; n = 20) was analyzed with the Student t-test.

§ p < 0.05; EIA for both groups (without VIPAR vs with VIPAR; n = 20) was analyzed with the Student t-test.

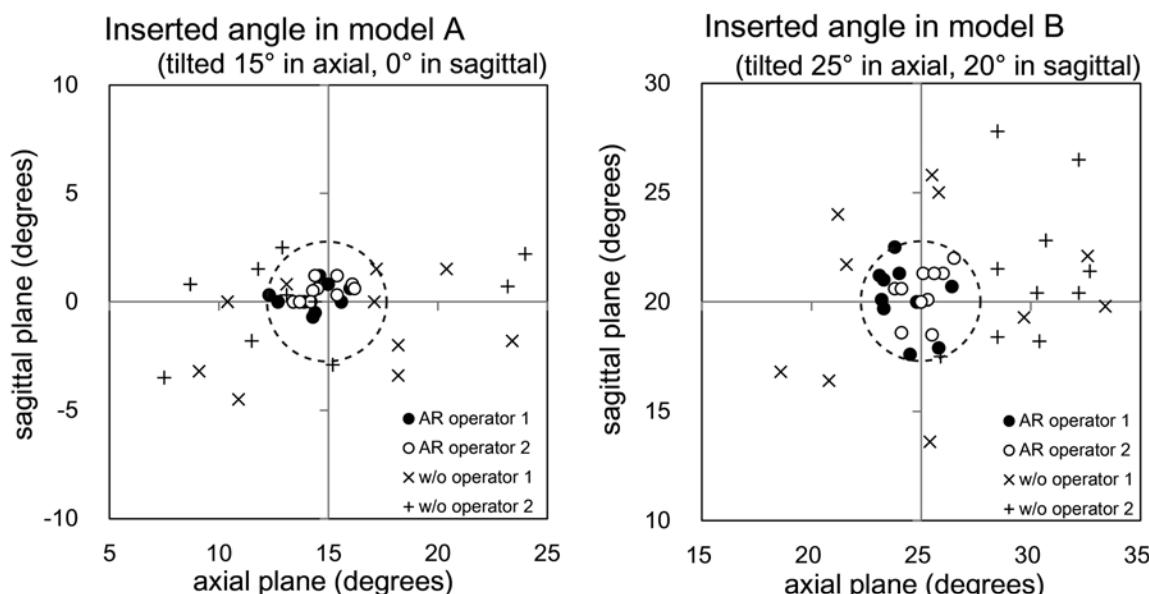
Postoperative CT revealed that the axial-plane EIA was 0.4° on the right and 1.0° on the left, while the sagittal-plane EIA was 1.2° on the right and 0.9° on the left (Fig. 7).

## Discussion

Rapid advances in medical imaging techniques due to the use of computers and related technological innovations in recent years has changed the paradigm in the field of computer-assisted spine surgery. Developments in information technology have enabled us to handle 3D data at a personal level and have facilitated the introduction of a CAS (computer-assisted surgery) system that uses consumer-grade computers.<sup>1</sup> In the present study, we introduced a new affordable AR guidance technique called

VIPAR, which was designed to require only commodity devices. Unlike other costly CAS systems such as CT-based navigation systems, VIPAR only requires a web camera and an HMD, which can be easily purchased for approximately \$1000 USD from a general market or online store. Using this system, a surgeon can insert a needle percutaneously into the pedicle while intuitively viewing the augmented needle trajectory through the HMD.

Previous studies have reported the accuracy of an experimental AR guidance system to be approximately 1 mm in error and have shown the system's promising potential as a clinical navigation device.<sup>4,10</sup> The results of the current study showed the error of the needle angle to be 0.96° in the axial plane when using a spine phantom. These experimental results were, however, measured



**Fig. 6.** Distribution of the inserted needle angle. **Left:** The needle trajectory in Model A was designed to be tilted 15° in the axial plane and 0° in the sagittal plane. The distribution pattern in the AR group is concentrated at the target angle, and all 20 trials exist inside a 2.5° circle (dashed circle). **Right:** The needle trajectory in Model B is designed to be tilted 25° in the axial plane and 20° in the sagittal plane. The distribution pattern in the sagittal plane is more scattered in Model B than in Model A.

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**TABLE 3: Summary of operative time and duration of radiation exposure related to VIPAR usage**

Case No.	Operative Time (mins)	Time for VIPAR (mins)*	Radiation Time	
			Total Exposure (secs)†	VIPAR (secs)‡
1	55	16	280	125
2	45	14	235	105
3	39	11	210	85
4	52	15	245	115
5	55	18	295	130
mean $\pm$ SD	49.2 $\pm$ 7.1	14.8 $\pm$ 2.6	253 $\pm$ 34	112 $\pm$ 18

\* Time needed for inserting the needles bilaterally using VIPAR.

† Total exposure including total fluoroscopy exposure time during surgery.

‡ Time needed for complete VIPAR procedures bilaterally.

with a strict positional adjustment between the real spine and virtual model; therefore, they cannot be expected in a clinical setting without a strict registration method. Unlike the pedicle screw insertion technique, which requires high-precision accuracy, the percutaneous transpedicular approach using fluoroscopy for a fractured thoracolumbar spine does not require such finesse. We have started applying our system to PVP in the thoracolumbar spine. Because of the roughness of the VIPAR registration method, needle insertion was accurate in the clinical cases than in the experimental trial. However, the system was used successfully by the surgeon as a virtual protractor that indicated the needle trajectory on the AR view, with easy registration using a sheet-type marker combined with conventional fluoroscopic guidance.

With regard to preoperative preparation, the use of an AR system has some advantages over other guidance methods. Several types of patient-specific templates have been reported, including the CT cut-out<sup>17</sup> or rapid prototyping template.<sup>19,22,26</sup> These physical devices, so-called tailor-made templates, are specific to an individual patient's anatomy and provide accurate guidance, but they require costly and time-consuming preparation. Because

AR systems require only a sterile sheet-type marker for physical preparation, the surgeon can use the system easily in any operative theater.

The greatest benefit of using an AR system is that it can provide the surgeon with intuitive hand-eye coordination by producing an augmented virtual target view of the patient space through the video see-through HMD. If AR technology was applied to navigation surgery such as spinal instrumentation placement or tumor resection, it could overcome the problem of current navigation systems that require the surgeon to deal with multiple areas of attention, the surgical site, and the display of the navigation system during the navigation task.<sup>4</sup> Furthermore, an AR system with a HMD can provide 3D information from any angle that the surgeon requires simply by moving the surgeon's head, and it can also provide a different augmented navigational view for each surgeon wearing an HMD. Augmented-reality guidance technology can also streamline the workflow of cumbersome spinal surgeries by allowing necessary medical data to be shared with each operator.

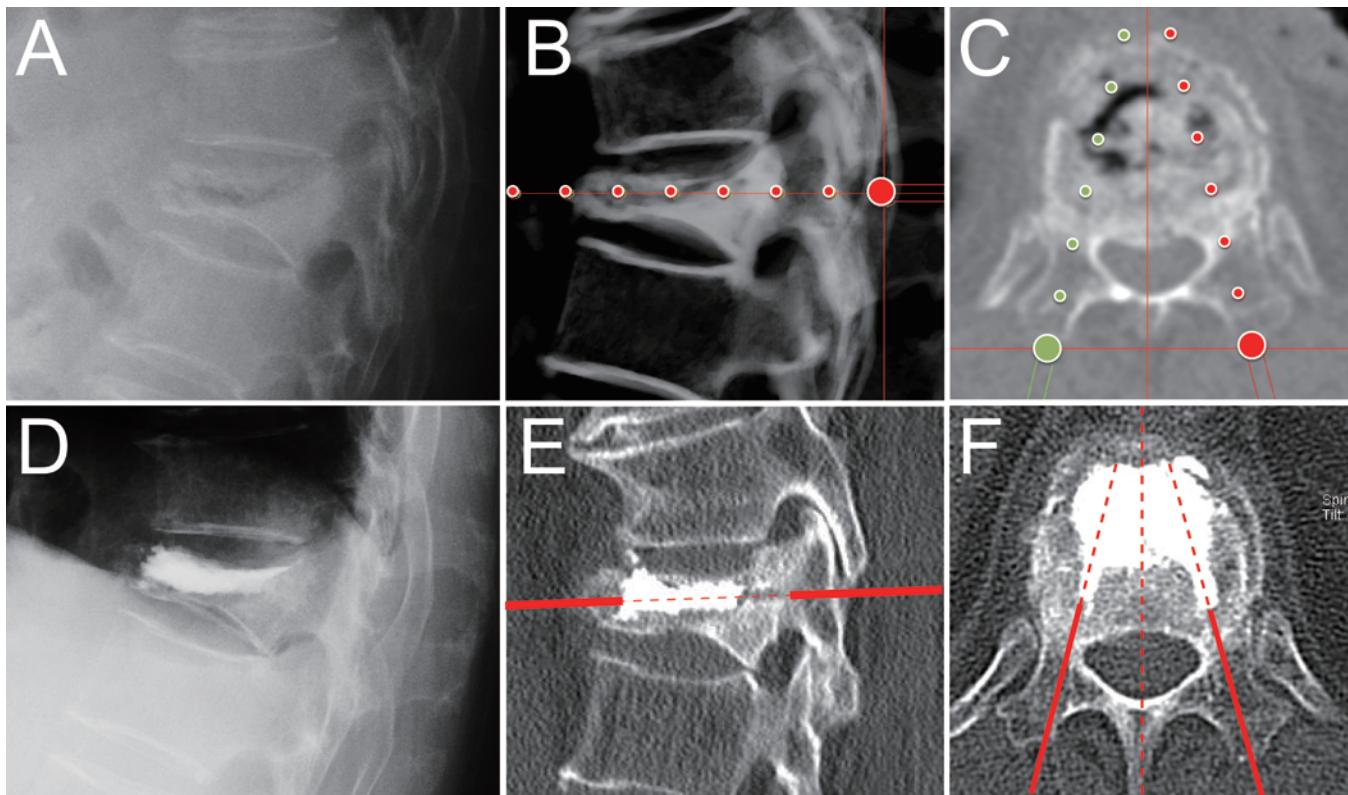
This study has some limitations. VIPAR does not allow for accurate mechanical registration as required in

**TABLE 4: Error of insertion angle in each case\***

Case No.	Approach	Axial Plane (°)		Sagittal Plane (°)		
		Attempted	Insertion	EIA (°)	Attempted†	Insertion
1	rt side	14	17.9	3.9	0	4.3
	lt side	16	18.5	2.5	0	4.4
2	rt side	17	14.7	2.3	0	0
	lt side	15	16.1	1.1	0	-0.2
3	rt side	16	13.9	2.1	0	-0.4
	lt side	16	14.8	1.2	0	0.7
4	rt side	16	13.0	3.0	0	-4.2
	lt side	15	18.4	3.4	0	-3.5
5	rt side	14	14.4	0.4	0	1.2
	lt side	14	15.0	1.0	0	0.9
mean $\pm$ SD		2.09 $\pm$ 1.3			1.98 $\pm$ 1.8	

\* Attempted = preoperative planned angle of the needle insertion (degrees); Insertion = actual insertion angle evaluated by CT scans.

† Attempted angle in the sagittal plane (0°) was designed to be parallel to vertebral axis.



**Fig. 7.** Images obtained in an illustrative case of a 68-year-old woman undergoing PVP. **A:** Preoperative radiograph showing an intravertebral cleft at T-12. **B and C:** Ideal needle trajectory analyzed using a 3D CT scan. **D:** Postoperative radiograph. The fractured T-12 vertebral body is percutaneously augmented with PMMA. **E:** Postoperative sagittal CT image. The needle path is indicated by the red line. The EIA (intended vs insertion angle) is  $1.2^\circ/0.9^\circ$  (right/left). **F:** Postoperative axial CT image. The EIA is  $0.4^\circ/1.0^\circ$  (right/left).

conventional CT-based navigation systems; consequently, the generated 3D needle trajectory was overlaid onto a detected marker placed on the patient's skin. This procedure, therefore, cannot be used for patients with more complicated deformities such as scoliosis involving vertebral rotation. Currently, the accuracy of needle insertion using VIPAR does not greatly exceed the accuracy of conventional fluoroscopy-assisted procedures. VIPAR partly supported the percutaneous transpedicular approach by indicating the 3D needle trajectory; however, confirmation of needle tip position, which is the key to ensuring safe needle insertion, was performed under fluoroscopic guidance, similar to conventional methods. The time required to complete the procedure, radiation exposure, and intraoperative complications did not differ from those reported in previous studies.<sup>13,16,20</sup> To profit from AR technology as an accurate navigational aid, further technical improvement is required. For example, combining AR with other registration methods such as intraoperative CT or fluoroscopy matching techniques<sup>24</sup> can improve the navigational ability of the system and enable wider use in more complicated cases that involve deformities. If these improvements are introduced, AR guidance technology can become a more effective assistive aid for PVP and other spinal instrumentation techniques, including the insertion of percutaneous pedicle screws in the cervical and thoracic spine, in the near future.

## Conclusions

The present study introduced a novel AR guidance system for use during the percutaneous transpedicular approach. The system can provide the surgeon with an ideal needle insertion point on the skin and a 3D trajectory of the needle through an augmented view on the video see-through HMD. Early clinical results and experimental accuracy in spine phantoms have demonstrated that VIPAR can successfully assist the surgeon as a virtual protractor by indicating the trajectory of the needle and preventing neurovascular complications during PVP of the thoracolumbar spine. Augmented-reality systems, which can integrate various types of medical information into the surgeon's field of view, can become a key technology that is integral to the development of a novel integrated medical guidance system.

## Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Abe, Ito, Abumi. Acquisition of data: Abe, Kato, Hyakumachi, Yanagibashi. Analysis and interpretation of data: Abe, Hyakumachi, Yanagibashi. Drafting the article: Abe. Critically revising the article: all authors. Reviewed

# Novel augmented reality-assisted percutaneous vertebroplasty

submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Abe. Statistical analysis: Abe. Administrative/technical/material support: Kato, Hyakumachi, Yanagibashi, Ito, Abumi. Study supervision: Sato, Hyakumachi, Yanagibashi, Ito, Abumi.

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