# 博士学位論文

## 胸部Ｘ線撮影におけるFowler 位の再現性を向上させるＸ線不透過角度計の開発

近 畿 大 学 大 学 院
医学研究科医学系専攻

**中　村　泰　典**

胸部Ｘ線撮影におけるFowler 位の再現性を向上させるＸ線不透過角度計の開発
中村泰典

Doctoral Dissertation

# Development of a radiopaque tiltmeter to improve reproducibility for Fowler's position on chest radiography

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課博

# 同　意　書

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論文題目

Development of a radiopaque tiltmeter to improve reproducibility for Fowler's position on chest radiography

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記

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# Development of a radiopaque tiltmeter to improve reproducibility for Fowler's position on chest radiography

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ABSTRACT

*Introduction:* We have developed a novel radiopaque tiltmeter (ROT) that can indicate patient tilt during a radiography examination and display it on X-ray images. This study evaluated the effect of variation of patient tilt on the reproducibility of Fowler's position for chest radiography and the accuracy of the ROT.
*Methods:* We evaluated the reproducibility of Fowler's position based on changes from the first day in the central venous catheter (CVC) tip position and the cardiothoracic ratio (CTR) with and without a digital tiltmeter to verify its efficacy in patients who underwent mobile chest radiography. The ROT contains radiopaque liquid consisting of white barium sulfate solution and oil and has a scale bar of 15°–75° with increments of 15° to indicate ROT tilt. The ROT tilt was increased from 10° to 80° in increments of 10°. We then evaluated (1) the difference between the ROT tilt and the tilt measured with a digital tiltmeter, and (2) the ROT tilt displayed on the X-ray image.
*Results:* With regard to reproducibility in Fowler's position, changes in the CVC tip position were 2.8 ± 3.9 mm and 10.7 ± 10.6 mm with and without the tiltmeter, respectively ($p < 0.05$) and the respective rates of change in the CTR were 0.7% ± 0.6% and 4.0% ± 2.1% ($p < 0.05$). Differences between the ROT tilt and the tilt measured by the digital tiltmeter were within ±2.5°. All ROT tilts displayed on the X-ray images were recognized exactly as each tilt.
*Conclusion:* Our novel ROT had the potential to accurately indicate patient tilt during chest radiography, which could be helpful in terms of reproducibility and precise follow-up.
*Implications for practice:* Use of the ROT for determination of patient tilt can improve reproducibility in Fowler's position, allowing more accurate serial X-ray imaging.


## Introduction

Mobile chest radiography is widely performed in clinical practice, particularly during follow-up of patients in the intensive care unit, for evaluation of pleural fluid volume,[1] central venous catheter (CVC) tip position,[2,3] and body fluid balance based on the cardiothoracic ratio (CTR).[4,5] The chest radiography in the supine position often underestimates the amount of pleural fluid and causes cephalad and peripheral redistribution of blood circulating in the cardiopulmonary system, which results in spreading of the cardiovascular structures.[4] For follow-up imaging in the intensive care unit and diagnosis of hypertrophic cardiomyopathy, the CTR can be measured when patients are in bed by obtaining anterior–posterior chest X-ray images and setting a cutoff value (e.g., a CTR of 60%).[4] Ideally, mobile chest radiography should be performed in a full erect position; when this is not possible, the patient should be placed in Fowler's position (i.e., in a semi-erect position) on the bed that is as close to the full erect position as the patient's clinical status permits.[4] Patient tilt, defined as an inclination from a supine to a semi-erect position, is also important during day-to-day follow-up with mobile chest radiography because parameters such as the cardiac silhouette, pleural fluid volume, CVC tip position, and CTR may affect the reproducibility of images.[1,2,4]

Poor reproducibility of patient tilt has three main causes. First, images may be acquired in a wide range of Fowler's positions, namely, low (15°–30°), semi (30°–45°), standard (45°–60°), and

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high (60°–90°).[6–8] Second, there may be variations in the set-up, such as patient tilt and X-ray tube tilt.[3,9] Third, there may be no information on patient tilt on previous X-ray images.[10]

A tiltmeter that can indicate patient tilt during set-up for radiography and display tilt on X-ray images is useful for reproducing Fowler's position and assists in making an exact diagnosis.[11,12] A metal ball tiltmeter (MET, X-Clometer; National Institutes of Health, Bethesda, MD, USA) can be used to confirm patient tilt and display this information on the X-ray image.[11] However, the error in patient tilt displayed on the X-ray image has been reported up to 25° when using a conventional MET in a standard to high Fowler's position,[11] which could affect the accuracy of the radiological diagnosis. We have developed a novel radiopaque tiltmeter (ROT, prototype; Akatsuki MFG Co., Ltd., Kyoto, Japan) that can indicate patient tilt during a radiography examination and display it on X-ray images. In this study, we investigated the effect of variation of patient tilt on the reproducibility of follow-up imaging, evaluated the accuracy of the ROT, and discussed whether its use can improve the reproducibility of Fowler's position for chest radiography.

## Methods

### *Efficacy of a tiltmeter for reproducibility of CVC tip position and CTR in Fowler's position*

We evaluated the reproducibility of the CVC tip position and CTR in Fowler's position with and without a tiltmeter to verify its efficacy. Five patients underwent a mobile chest radiography examination on 6 consecutive days (3 consecutive days with and 3 consecutive days without use of a digital tiltmeter [DI-100M, compact digital level; Akatsuki MFG Co., Ltd.]). According to the patients' medical records, there were no dialysis sessions or changes in procedures during the 6 consecutive test days. The study protocol was approved by the Ethical Committee of the University Hospital, Kyoto Prefectural University of Medicine (approval number: ERB-C-2008). We obtained informed consent to participate from patients.

The Patients, who were referred by the chest radiography with Fowler's position for the postoperative follow-up such as cardiac silhouette, pleural fluid volume, CVC tip position, and CTR, were included in the study. Patients on a ventilator were excluded because their condition may change from day to day, which could affect the reproducibility of measurements. The exposure conditions were adjusted to the patient's body thickness. The tube voltage was constant at 80 kVp, while the tube current and exposure time ranged from 1.6 to 2.5 mAs. The values for the CVC tip position and CTR on the first day were defined as the reference values. Differences between the reference values and each value on the remaining 2 days were evaluated with or without the tiltmeter. The CVC tip position was defined as the vertical distance between the heights of the CVC tip and the tracheal bifurcation.[13] The CTR was calculated as the ratio of the maximal width of the cardiac shadow to the maximal internal thoracic width.[4] Measurements obtained with and without the digital tiltmeter were compared using the Wilcoxon signed-rank test. A $p$-value of $< 0.05$ was considered statistically significant.

### *Design of the ROT*

Fig. 1 shows the design of the ROT, which includes a scale ranging from 15° to 75° in increments of 15° (defined as the ROT tilt). The internal height is set to 31.0 mm (8.0 mm [width] × 19.0 mm [length] × 31.0 mm [height]) as the minimum size that could determine a tilt of 10°, and the external dimensions are 14.0 mm × 25.0 mm × 37.0 mm. The ROT contains a radiopaque contrast agent of a white barium sulfate solution at a concentration of 200 w/v%. The contrast agent is mixed with oil to clearly define the barium surface and to reduce the wettability of barium to polystyrene. Each scale position is calculated as follows:

1. $\theta$ is defined as the tilt between the bottom of the ROT and the liquid surface. $X_\theta$ and $Y_\theta$ indicate the length of the bottom of the liquid in the ROT and the height of the liquid (Fig. 2). For a $\theta$ value of 10°, $X_{10}$ is 34.5 mm, and $Y_{10}$ was calculated from Equation (1) (Fig. 2A):

$$Y_{10} = X_{10} \times \tan 10^\circ (\mathrm{mm}) \tag{1}$$

$S$ is then defined as the area of the triangle formed by the white barium sulfate solution on the right-side view of the ROT in Fig. 2A, based on Equation (2):

$$S = \frac{1}{2} \times X_{10} \times Y_{10} \tag{2}$$

2. The area $S$ is constant for each tilt. For the $\theta$ values of 10°, 15°, 30°, and 45° in Fig. 2A, the shape of the white barium sulfate solution on the right-side view corresponds to the triangle, and $X_\theta$ is determined from Equation (3):

$$X_\theta = \sqrt{2S \times \frac{\cos\theta}{\sin\theta}}\,(\mathrm{mm}) \tag{3}$$

3. For the $\theta$ values of 60° and 75° in Fig. 2B, $Y_\theta$ is 19 mm, and the shape of the white barium sulfate solution on the right-side view corresponds to the trapezoid. $X_\theta$ is calculated from Equation (4):

$$X_\theta = \frac{S}{19} + \frac{\cos\theta}{2\sin\theta} \times 19\,(\mathrm{mm}) \tag{4}$$

4. The scale positions for 15°–75° are 28.0, 19.1, 14.5, 11.0, and 8.1 mm, respectively, from the base (Fig. 1).

Fig. 3 shows a schematic view of each ROT tilt from 15° to 75°. The ROT tilt can be confirmed by observing the same height for the liquid surface in the front-side view (A) and right-side view (B) of the ROT. In addition, the ROT tilt can be recorded on the X-ray image by the projected liquid surface (C).

### *Accuracy of ROT tilt during set-up for radiography*

We evaluated the accuracy of the ROT tilt during set-up for radiography. The detector was set on the bed (Transfer Stretcher KK-725 Series, Paramount Bed, Tokyo, Japan), and the ROT tilt was increased to 10°, 20°, 30°, 40°, 50°, 60°, 70°, and 80° using the ROT with the scale of 15°, 30°, 45°, 60°, and 75° (Fig. 1) placed on the center of the detector. The differences between these ROT tilts and the tilts measured by a digital tiltmeter (DP-90; Levelnic, Niigata Seiki Co., Ltd., Niigata, Japan) were evaluated by three evaluators at three times. The same measurements were obtained using a MET (MET tilt), as described in a previous report,[11] for comparison with the accuracy of the ROT tilt during set-up for radiography. Data were evaluated by the mean ± 1 standard deviation and the average of differences between the ROT or MET tilts and the tilts measured with the digital tiltmeter.

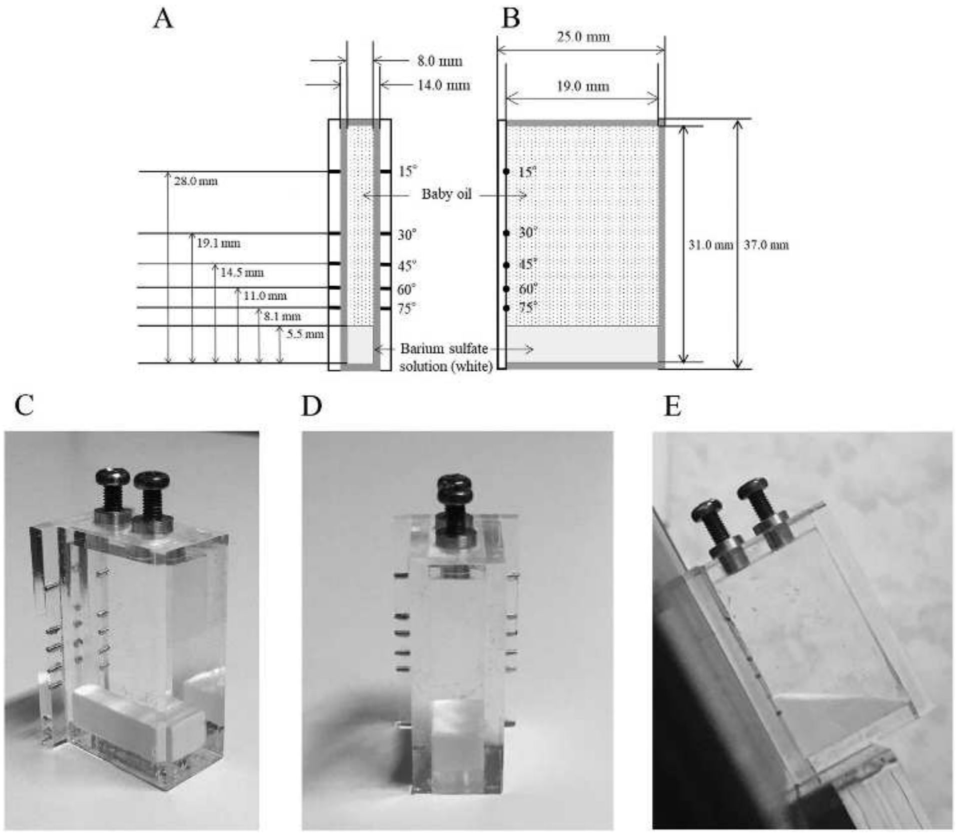


**Figure 1. Design of the ROT**. A, Schematic front-side view. B, Schematic right-side view. Based on a 2.0 mm polystyrene sheet, the internal dimensions were 8.0 mm (width) × 19.0 mm (length) × 31.0 mm (height). The heights at tilts of 15°, 30°, 45°, 60°, and 75° were 28.0, 19.1, 14.5, 11.0, and 8.1 mm, respectively. C, External view. D, Front-side view. E, Right-side view at a ROT tilt of 60°. The level of the radiopaque material indicates a tilt of 60°. ROT: radiopaque tiltmeter.

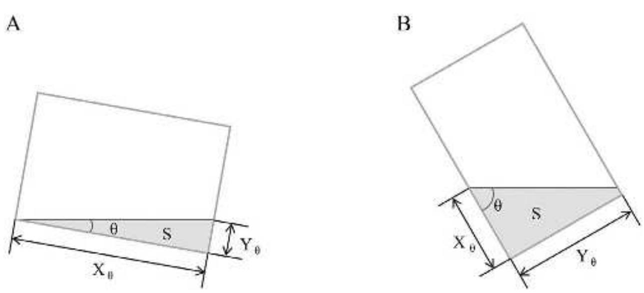


**Figure 2. Illustrations for calculations of the scale on the ROT**. A, $\theta = 15°, 30°, 45°$. B, $\theta = 60°, 75°$. $X_\theta$ and $Y_\theta$ are the lengths of each side for a tilt of $\theta$. $S$ is the area of the white barium sulfate solution.

*Accuracy of display ROT tilt on X-ray images*

We evaluated the accuracy of the ROT tilt displayed on the X-ray images (defined as display ROT tilt). A flat panel detector (FPD; 14 × 17 inches, wireless direct-conversion FPD system; Konica Minolta, Tokyo, Japan) was set on the bed and the ROT tilt was increased from 10° to 80° in increments of 10°. The ROT was placed on the center of the FPD, and the X-ray tube (0.6/1.2 P324 DK-85; Shimadzu, Kyoto, Japan) was set to each ROT tilt. The X-rays were then incident on the center of the ROT, and the display ROT tilts on the X-ray images were obtained. Three evaluators estimated the display ROT tilts from 10° to 80°.[11] The X-ray tube tilt was calibrated with a digital tiltmeter before acquisition of X-ray images. The exposure conditions were set as follows: tube voltage, 80 kVp; tube current, 400 mA; and exposure time, 10 ms.[14] The source-to-image detector distance was set to 100 cm.[15] Fig. 4A shows an example of the 60° setting for evaluation of the accuracy of the display ROT tilt on X-ray images.

## Results

*Efficacy of a tiltmeter for reproducibility of CVC tip position and CTR in Fowler's position*

For the same patients, the mean differences in CVC tip position over 3 days were 2.8 ± 3.9 mm with the tiltmeter and 10.7 ± 10.6 mm without the tiltmeter, the respective mean differences of change in the CTR were 0.7% ± 0.6% and 4.0% ± 2.1% (Table S1). The differences in both the CVC tip position and the CTR were reduced significantly ($p < 0.05$) when using the digital tiltmeter (Fig. 5).

*Accuracy of ROT tilt during set-up for radiography and displayed on X-ray images*

Table 1 summarizes the differences between the ROT or MET tilts and the tilts measured with the digital tiltmeter. The maximum difference was 2.5° at 70° for the ROT tilt and 5.3° at 60° for the MET tilt. The average of the difference between the ROT or MET tilts and tilts measured with the digital tiltmeter was 0.7° for the ROT tilt and 1.1° for the MET tilt. The difference of the ROT tilt was similar to that of the MET tilt.

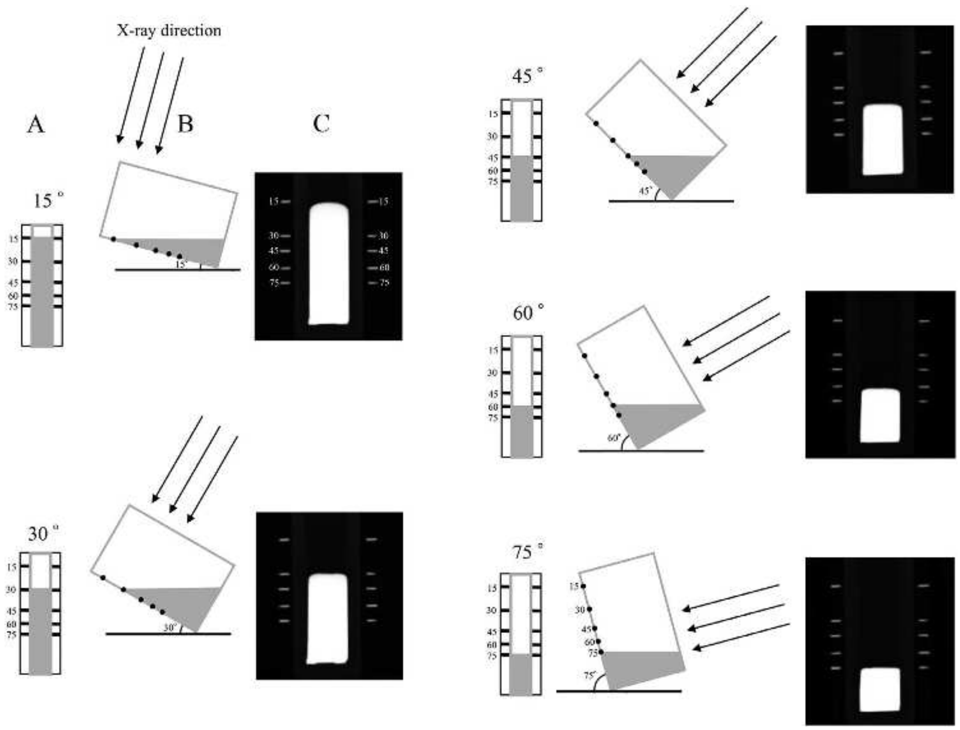


**Figure 3. Schematic diagram for ROT tilt from 15° to 75°**. The arrows indicate the direction of the incident X-ray beam. A, Front-side view of the ROT from the direction of the incident X-ray beam. B, Right-side view. C, ROT displayed on X-ray images. For a patient tilt of 15°, the level of the radiopaque material is displayed as a mountain-like shape. The highest tip on the scale indicates a patient tilt of 15°. ROT: radiopaque tiltmeter.

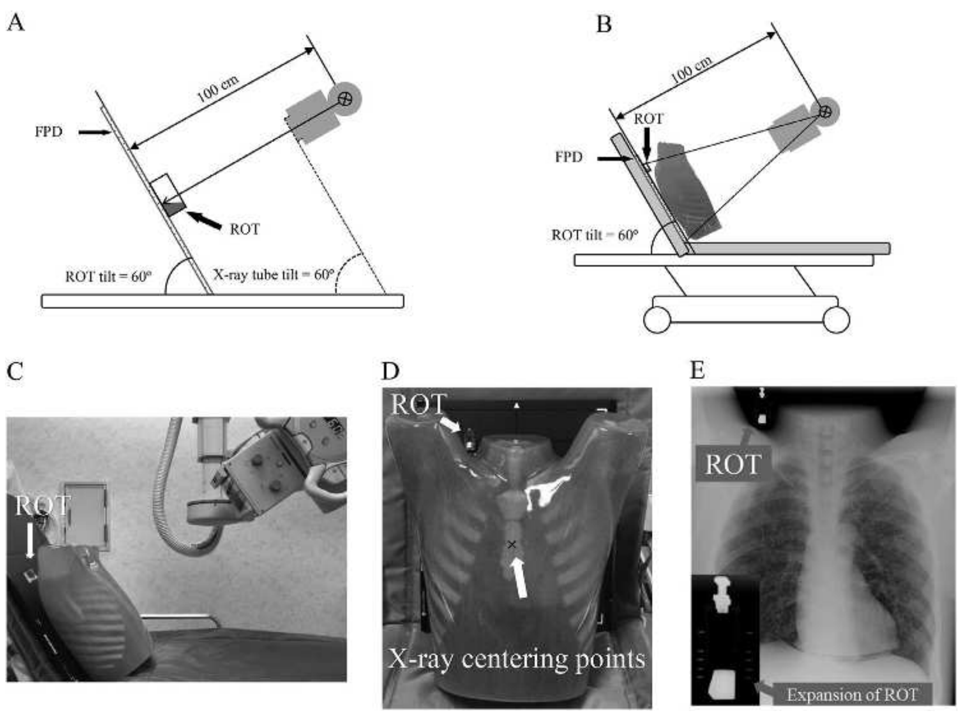


**Figure 4. Experimental set-up when using the FPD and ROT with a tilt of 60°**. A, X-ray tube tilt is defined as the dihedral angle between the plane of the X-ray tube collimator and the bed (60° in this case). B, C, and D Set-up using the chest phantom. The ROT was placed on the right side of the neck of a chest phantom. E, X-ray images showing the chest phantom and ROT. FPD: flat panel detector, ROT: radiopaque tiltmeter.

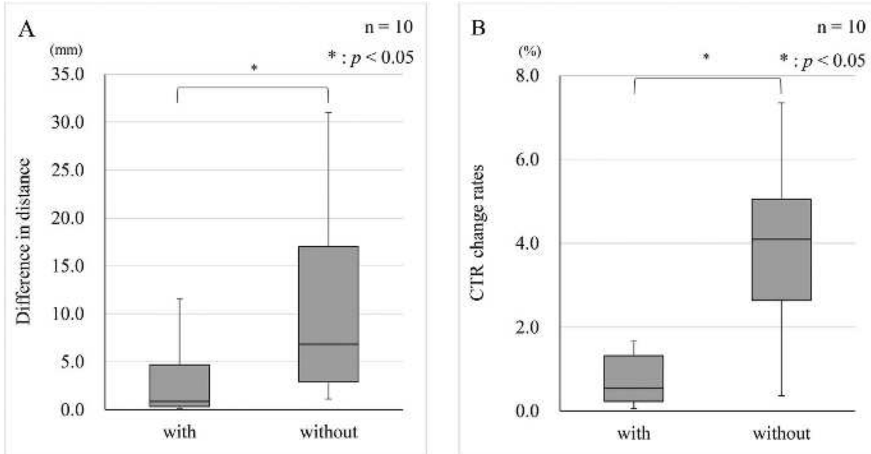


**Figure 5. Comparison of the central venous catheter tip position and the cardiothoracic ratio with and without a digital tiltmeter**. A, central venous catheter. B, cardiothoracic ratio. CVC: central venous catheter, CTR: cardiothoracic ratio.

**Table 1**
Differences between ROT or MET tilts and tilts measured with a digital tiltmeter during set-up for radiography.

| ROT tilt (degrees) | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|---|---|
| Measurement | 11.0 ± 0.5 | 20.3 ± 0.9 | 30.1 ± 0.5 | 39.6 ± 1.1 | 49.8 ± 0.5 | 59.7 ± 0.8 | 69.6 ± 1.2 | 79.1 ± 0.8 |
| Difference | 1.02 | 0.74 | 0.38 | 0.84 | 0.40 | 0.57 | 0.98 | 0.99 |
| MET tilt (degrees) | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
| Measurement | 9.9 ± 1.2 | 19.8 ± 0.7 | 30.0 ± 0.7 | 39.4 ± 1.7 | 49.9 ± 0.8 | 61.1 ± 1.9 | 69.9 ± 1.4 | 79.7 ± 2.4 |
| Difference | 1.02 | 0.58 | 0.47 | 1.52 | 0.68 | 1.44 | 1.15 | 1.85 |

ROT: radiopaque tiltmeter, MET: metal ball tiltmeter, Measurement: mean ± 1 standard deviation, Difference: average of the differences (absolute values) between ROT or MET tilts and tilts measured with the digital tiltmeter.

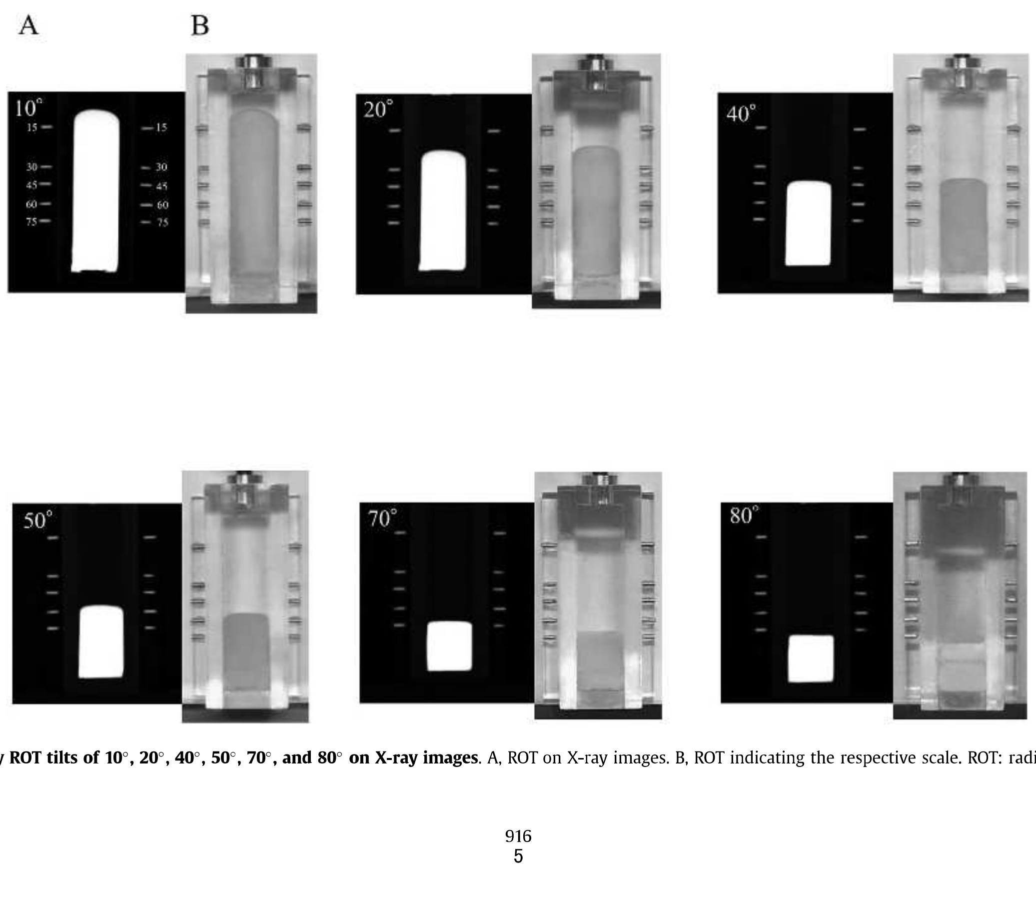


**Figure 6. Display ROT tilts of 10°, 20°, 40°, 50°, 70°, and 80° on X-ray images**. A, ROT on X-ray images. B, ROT indicating the respective scale. ROT: radiopaque tiltmeter.

Fig. 6 shows each display ROT tilt on X-ray images. The display ROT tilt corresponded to the tilt from 10° to 80° with 100% agreement.

## Discussion

In this study, we found that our newly developed ROT provided a highly accurate indication of patient tilt in Fowler's position during mobile chest radiography. Moreover, patient tilt could be displayed on the X-ray image, which allowed for exact determination of tilt. Therefore, this ROT could be helpful in terms of reproducibility of the CVC tip position and CTR and useful when chest X-ray images need to be obtained for precise follow-up in Fowler's position.

As shown in Fig. 5A, the change in CVC tip position was reduced by approximately one-fifth when using the tiltmeter. The difference in the rate of change in the CTR with and without the tiltmeter averaged 5.6%, as shown in Fig. 5B. Sahin et al. have pointed out that changes in the CTR on X-ray images because of variation in patient tilt on mobile chest radiography may result in incorrect interpretation.[4] In our study, the rate of change in the CTR was also reduced by approximately one-fifth when the tiltmeter was used. Thus, the tiltmeter is need for the accurate diagnosis.

The white barium sulfate solution in the ROT can indicate tilt within ±2.5° (Table 1). In terms of the accuracy of ROT tilt during the set-up for radiography, the difference of the ROT tilt was comparable to that of the MET tilt. Therefore, there were no visibility issues during radiography, even though the thickness of the liquid decreased at low tilts (e.g., 10° and 20°).

The display ROT tilt on the X-ray images corresponded exactly to those for patient tilt. When using the conventional MET device, the accuracy of the display MET tilt on the X-ray image deteriorates as the patient tilt increases from a standard Fowler's position to a high one, with errors of up to 25°.[11] It was considered that the distance between the metal sphere in the MET indicating the tilt and the detector surface increased with increasing patient tilt and that tilting of the X-ray tube and beam divergence, causing the large errors on X-ray images.[11] Therefore, we devised a ROT in which the surface of the radiopaque material is in contact with the surface of the detector at all tilts to overcome that issue (Fig. 3). In the cases of the low ROT tilts (e.g., 10° and 20°), the level of the radiopaque liquid is displayed as the mountain-like shape (Fig. 6); however, those display ROT tilts can be also recognized due to the design with large intervals of the scale (Fig. 1). As a preliminary measurement, we also evaluated the accuracy of the display ROT tilt when the X-ray tube was tilted to −10°, −5°, +5°, and +10° from each ROT tilt. In this experiment, the display ROT tilt matched the ROT tilt with 99.0% agreement, indicating that tilting of the X-ray tube and beam divergence do not impact the accuracy of the display ROT tilt. As an additional analysis, we placed the ROT on the right side of the neck of a chest phantom (N1 LUNGMAN; Kyoto Kagaku, Kyoto, Japan) (Fig. 4B–E) and measured the accuracy of the display ROT tilt on X-ray images. We found that the ROT tilt of the phantom matched the display ROT tilt with 95.8% accuracy.

The findings of this study suggest that use of an accurate tiltmeter improves the reproducibility of patient tilt, which could allow more precise and consistent diagnosis and observations. The ROT is expected to have the following advantages: radiographers will be able to check patient tilt during set-up and on previous X-ray images for serial examinations; physicians will be able to make more accurate diagnoses consistently during follow-up; and the need for unnecessary additional examinations due to irreproducibility of patient positioning can be avoided.

In the clinical situation, the reasons for variations of such as CTR and CVC tip position are complex because anterior–posterior chest X-ray images obtained in Fowler's position are influenced by rotation, lung volume, and source-detector and source-object distances. Our current ROT cannot consider all of these variations, although the tiltmeter can mitigate the variations in CTR and CVC tip position during follow-up to some extent, as shown in Fig. 5. Further revisions to the ROT design, such as inclusion of a visible difference in the right-left point of the radiopaque level and verification of dependency on the source-to-image-ditector distance generally used in mobile chest radiography,[16] are needed to overcome this limitation.

## Conclusion

Our novel ROT has demonstrated the potential to provide accurate measurements of patient tilt in Fowler's position during mobile chest radiography. This device could be helpful for reproducibility of this position during serial radiography examinations.

## Conflict of interest statement

The authors declare no potential conflicts of interest with respect to the research and authorship of this article.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radi.2022.06.008.

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# Supplementary Material

**Table S1. CVC tip position and CTR data obtained with and without a digital tiltmeter for the same five patients on 6 consecutive days**

| | | Without a digital tiltmeter | | | | | With a digital tiltmeter | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CVC tip position | | CTR | | | CVC tip position | | CTR | |
| Patient | Day | Data (mm) | Difference (mm) | Data (%) | Difference (%) | Day | Data (mm) | Difference (mm) | Data (%) | Difference (%) |
| A | 1 | 6.70 | | 47.74 | | 4 | 6.80 | | 46.17 | |
| | 2 | 8.20 | 1.50 | 48.11 | 0.36 | 5 | 6.70 | 0.10 | 46.93 | 0.77 |
| | 3 | 11.40 | 4.70 | 46.17 | 1.58 | 6 | 7.70 | 0.90 | 47.83 | 1.67 |
| B | 1 | 16.90 | | 56.34 | | 4 | 25.40 | | 55.46 | |
| | 2 | 41.20 | 24.30 | 60.62 | 4.29 | 5 | 25.60 | 0.20 | 55.21 | 0.24 |
| | 3 | 10.10 | 6.80 | 58.66 | 2.32 | 6 | 25.20 | 0.20 | 55.58 | 0.12 |
| C | 1 | 49.70 | | 53.23 | | 4 | 51.20 | | 55.30 | |
| | 2 | 69.70 | 20.00 | 57.14 | 3.90 | 5 | 57.60 | 6.40 | 53.88 | 1.42 |
| | 3 | 80.70 | 31.00 | 56.81 | 3.58 | 6 | 39.60 | 11.60 | 53.82 | 1.48 |
| D | 1 | 21.30 | | 63.25 | | 4 | 8.10 | | 62.43 | |
| | 2 | 29.30 | 8.00 | 57.12 | 6.13 | 5 | 8.80 | 0.70 | 62.21 | 0.22 |
| | 3 | 20.20 | 1.10 | 58.16 | 5.09 | 6 | 7.30 | 0.80 | 61.41 | 1.02 |
| E | 1 | 44.50 | | 55.88 | | 4 | 50.20 | | 65.52 | |
| | 2 | 51.40 | 6.90 | 60.82 | 4.94 | 5 | 55.90 | 5.70 | 65.82 | 0.30 |
| | 3 | 42.20 | 2.30 | 63.23 | 7.35 | 6 | 51.80 | 1.60 | 65.58 | 0.06 |

Five patients underwent mobile chest radiography examination on 6 consecutive days (3 consecutive days with and 3 consecutive days without use of a digital tiltmeter). The reproducibility of the CVC tip position and CTR in Fowler's position with and without the digital tiltmeter was evaluated. The values for the CVC tip position and CTR on the first day were defined as the reference values. Differences between the reference values and each value on the remaining 2 days were evaluated. The CVC tip position was defined as the vertical distance between the height of the CVC tip and the height of the tracheal bifurcation.

CVC = central venous catheter, CTR = cardiothoracic ratio.