

# The Impact of Vertical Off-Centring, Tube Voltage and Phantom Size on CT Numbers: An Experimental Study

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## Research Article

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# Abstract

**Objectives:** This pilot experimental study explores the effect of vertical off-centring on CT numbers in combination with various tube voltages and phantom sizes.

**Methods:** A CIRS Model 062 Electron Density and Combined Head and Body phantom underwent imaging using a Siemens Emotion 16-slice CT and GEMINI GXL scanners. Uniformity was evaluated as a function of vertical off-centring (20, 40, 60, and 80 mm above the gantry iso-centre) using different phantom sizes and tube voltage for ROI positions across the X and Y axis of each phantom. CT number change was assessed by comparing the measured values between anterior (upper) versus posterior (lower) ROIs.

**Results:** The results showed that vertical off-centring and phantom size could account for 92% of the recorded variance and resultant CT number change. The uniformity test recorded a maximum change of 27.2 and 14 HU for peripheral ROIs at 80 mm phantom shift above the gantry iso-centre using the GEMINI GXL and Siemens scanners, respectively. The absolute CT number differences between anterior and posterior ROIs were 13.7 for the 30 cm phantom and 4.8 for the 20 cm phantom at 80 mm vertical off-centring. The most remarkable differences were observed at lower tube voltages.

**Conclusions:** It is essential to highlight the significance of optimal patient centring for CT examinations and the consequences of CT numbers variation on clinical decision making. Phantom off-centring and ROI location have been demonstrated to affect CT number uniformity in this pilot experimental study. This was more evident at peripheral phantom areas, lower tube voltages and larger phantom size.

## Introduction

Computed tomography (CT) has long been considered an important imaging modality providing characterisation of the composition and anatomical location of soft-tissue lesions [1]. The reliability of Quantitative CT (QCT) to assess diseases is primarily dependent upon the accuracy of the CT number (or the Hounsfield Unit (HU)) of the tissue scanned [2–4]. In CT, the Hounsfield scale is used to represent all body tissues according to a linear density scale, with water arbitrarily assigned a value of zero HU, and all other values computed according to the following formula [5]:

$$HU = \frac{\mu_{tissue} - \mu_{water}}{\mu_{water}} \times 1000 \quad (1)$$

However, it is widely accepted that CT numbers are influenced by several factors, including scanner design and calibration, reconstruction algorithms, beam hardening artifacts, body size, object orientation, the tube voltage, and object off-centring [6–10]. These factors are known to cause CT number variability, which can significantly affect the reliability of the resultant data [11]. Importantly, variability in the CT number can affect the sensitivity and specificity of lesion detection and characterisation which are based on the CT number threshold [12], such as adrenal and renal masses [13–15]. Furthermore, the calculated

radiation dose for therapy may also be affected by CT number variability because dose calculation depends primarily on the CT number in obtaining mass density of lesion under treatment [16].

Body size is also considered a factor that contributes to the inaccuracy of the CT number as a result of a beam hardening effect [17] and scanner calibration [18]. Consequently, various beam hardening correction schemes are incorporated into modern clinical scanners. However, these corrections are calibrated with one specific body size and tube voltage only [18].

In CT, optimal patient positioning requires the patient to be oriented at the iso-centre of the scanner gantry. However, it is well known that off-centring in the clinical setting commonly occurs, most notably in the vertical direction, below the gantry iso-centre [19, 20]. Correct centring is important as bowtie filters are used to adjust the distribution of the beam based on scanned body attenuation. Even beam distribution is typically achieved by restricting the beam intensity at the periphery, thus allowing a higher central beam intensity [21]. To maximum the bowtie filter effect, patient centring needs to be precise.

Several studies have shown that inappropriate or suboptimal patient centring within the CT scanner gantry affects both image quality and radiation dose [22–26]. To our knowledge, however, there are no publications investigating the CT number variation as a function of the combined influence of vertical off-centring at different tube voltages and phantom sizes. This paper will compare these parameters across two CT scanners.

## Materials And Methods

A combined head and body system performance phantom supplied with the GEMINI GXL system and a CIRS Model 062 were used in this study. The head phantom construction consisted of a 20 cm diameter polyvinyl chloride (PVC) cylinder filled with water with three sections: a multi-pin layer, physics and water layer. For the purpose of this study, only the water layer from the head phantom was scanned to enable direct comparison. The CIRS Model 062 phantom is made of water-equivalent material and consists of two nested disks (outer and inner) measuring 18 x 18 x 5 cm simulating a head and 33 x 27 x 5 cm (average of 30 cm in diameter) simulating an abdomen. In order to simulate a water phantom, all inserts were replaced with water balloons. This eliminated CT number interference from neighbouring inserts.

The combined head and body phantom was initially scanned at the iso-centre using a GEMINI GXL system, at 90 kVp, 250 mAs with 5 mm slice thickness. To mimic clinical imaging, a routine helical abdomen protocol was used with a large bowtie filter, 0.75-s gantry rotation time, 0.9 Pitch, 6 x 1.5 collimation, and 50 cm field of view (FOV). The table was raised 20, 40, 60, and 80 mm above the gantry iso-centre. Scanning was repeated three times for each displacement to determine reproducibility by identifying spurious results. Imaging was then repeated at 120 and 140 kVp, using the same scanning protocol parameters and table movements due to scanner limitations (PET functionality), off-centring was only possible in the vertical direction above the gantry iso-centre, which is acknowledged as a limitation of the study.

The CIRS Model 062 phantom was scanned using a Siemens Emotion 16-slice System, with the same experimental setup to enable comparison between the two scanners. Three kVp sets were predetermined by the manufacturer at 80, 110, and 130 kVp.

Uniformity testing is performed by evaluating the CT number for uniform water or water-equivalent phantom. COVID-19 restrictions and the geographical location of the scanners used in this study meant that the same phantom was unable to be scanned at both locations. However, the performance of the two phantoms should be the same as both are water phantoms. The phantom supplied with the GEMINI GXL system is a water-filled test object (or containing liquid water) and the CIRS phantom is constructed originally from a water equivalent material meeting the requirement of the test [27]. The CT number uniformity was examined at variable tube voltages and phantom sizes (18, 20, and 30 cm), using Image J software, to evaluate the impact of beam hardening artifacts [28]. Regions of interest (ROIs) in this test were positioned across the image in both X and Y axis and included one ROI that was placed in the centre of the phantom (Fig. 1). The peripheral ROIs were placed 1 cm from the phantom edge to exclude any influence from the PVC housing of the phantom on CT number [29].

The differences in the CT number were calculated between corresponding anterior (upper) and posterior (lower) ROIs in both axis to investigate any differences associated with phantom off-centring and ROIs locations.

## Statistical Analysis

The statistical paired *t*-test was used to compare the CT number change between the two different scanners and vertical off-centring positions (above the gantry iso-centre). The significance of the impact of phantom off-centring, and body size on the CT number was evaluated using analysis of covariance (ANCOVA). A *p*-value of < 0.05 was considered statistically significant.

## Results

### CT Number Uniformity

The *t*-test demonstrated a significant difference between CT number uniformity performance for both scanners ( $t = 31.6$ ,  $df = 10.96$ ,  $p < 0.001$ ). The GEMINI GXL system demonstrated the greatest inconsistency. At the off-centring 80 mm above iso-centre, the CT number changed at the peripheral ROIs was up to 17.1 HU cross the X axis at 90 kVp. From the gantry iso-centre, there was a symmetrical type change in the CT number across the phantom when ROIs had shifted away from the phantom centre; for example, the recorded HU were 16.1 and 16 for peripheral ROIs in the X axis. However, the CT number change was 15.5, and 17.1 for the same peripheral ROIs when the phantom was 80 mm vertically off-centred. A cross the Y-axis, the greatest CT number change recorded for the peripheral ROIs was 27.2 HU at 80 mm vertical off-centring and 90 kVp. Furthermore, vertical off-centring had more influence on CT number symmetry across the Y-axis compared to the X-axis as the measured CT number change for

peripheral ROIs were 17.7 and 14.9 HU (at +Y and -Y-axis respectively), while 27.2 and 13 HU were recorded at 80 mm off-centring for the same measured ROIs.

The Siemens system performance was more consistent for both phantom sizes at the iso-centre. However, for the 30 cm phantom at 80 mm vertical off-centring and 80 kVp, a change in the CT number was found to be more prominent at peripheral ROIs, reaching a maximum of 11.1 HU at the X-axis and 14 HU in the Y-axis. The symmetry of CT number change at peripheral ROIs was not influenced by vertical off-centring across the X-axis (+X and -X-axis), changing from 0.7 and 1.0 HU at the gantry iso-centre to 11.1 and 11 HU at 80 mm off-centring and 80 kVp. At the same time, a maximum 14 and 2.2 HU change was recorded across the +Y and -Y-axis at 80 mm vertical off-centring compared to 3.3 and 6.1 HU at the gantry iso-centre, Fig. 2. This is indicative of CT number uniformity being influenced by two factors: vertical off-centring and phantom size.

## **The combined effect of vertical off-centring and phantom size on CT number**

A plot of the CT number change at various vertical off-centring is shown in Fig. 3. Based on body size, the 30 cm CIRS phantom (combined discs) demonstrated the greatest CT number change when the phantom was vertically off-centred by 80 mm and imaged at lower tube voltage (80 kVp). After adjustment for CT number change, the covariate, phantom size, was shown to be significantly related to CT number change with vertical off-centring ( $F(2,39) = 228.68, p < 0.001$ ). Adjusted R-squared explained that vertical off-centring and phantom size could account for 92% of the recorded variance and resultant CT number change between images.

In Fig. 4 (a), ROI A showed a decrease in the average CT number when the phantom shifted vertically and further away from the gantry iso-centre. At the same time, when ROI B was similarly off-centred, moving closer to the beam centre, a slight increase in the average CT number for the first two vertical increments steps was evidenced. The average CT number of the lower and the upper ROIs increased by 4.8 HU at 90 kVp, 4 HU at 120 kVp, and 4.7 at 140 kVp when the phantom was vertically off-centred to 80 mm (Fig. 4b).

Two ROIs were located peripherally at the anterior and posterior abdominal aspect of the CIRS phantom (Fig. 5a). At 110 kVp and with an 80 mm vertical shift, the mean difference in the CT number compared to the gantry iso-centre was - 5.3 HU in the anterior ROI, and 4.3 HU in the posterior ROI. Further, the absolute mean differences in the CT number between the anterior and posterior ROIs was 10.7 HU at 80 kVp and 6.8 HU for 110 and 130 kVp with an 80 mm vertical off-centring (Fig. 5b). The CT difference was observed to be greater at lower tube voltage and as the phantom was moved further from the iso-centre.

## **Tube Voltage**

Unlike the GEMINI GXL system, data for the Siemens system showed that the tube voltage had no effect on the CT number for water at the gantry iso-centre. It was also observed that the CT numbers remained close for both higher voltage sets (110 and 130 kVp), whilst for the GEMINI GXL system, the CT number

was closer for both 90 and 120 kVp sets under-examined conditions (Fig. 2). Generally, the vertical off-centring in both systems had a more dramatic influence on CT number change at low tube voltage.

## Discussion

### CT number uniformity

There is no universally accepted value for CT number uniformity; however, the International Electrotechnical Commission (IEC) recommends the mean CT number of the central ROI should not deviate from the manufacturer's specified value by more than  $\pm 4$  HU for each material measured [29] and that the difference in uniformity do not exceed more than 2 HU from the baseline value [30].

The Siemens system demonstrated superior uniformity performance in comparison to the GEMINI GXL system, most likely due to the incorporation of beam hardening correction software. Typically, these corrections are automatically applied for various body sizes. However, the uniformity test results were not the same between units when the respective phantoms were off-centred from the gantry iso-centre. This indicates that beam hardening corrections are corrected and functional at the gantry iso-centre only.

### Vertical off-centring and phantom size

The current study showed that the 20 cm water phantom had no more than a 0.5 HU change in CT number with up to 60 mm of vertical off-centring when the ROI was located at the phantom centre. The results by Kalra et al. (2009) concur with these results [26]. Furthermore, a study by Sukupova et al. (2016) found that within 100 mm of vertical off-centring, there was no substantial change in the CT number; however, with 140 mm or more vertical off-centring, a 20 HU change was recorded [31]. These findings can be explained whereby the amount of off-centring required to cause a CT number change for a ROI will depend on the alignment of phantom geometry and the bowtie filter size. For instance, the CT number for the 30 cm phantom demonstrated a change of 4.3 HU at 80 mm off-centring and 80 kVp compared to 1.4 HU for the 18 cm phantom.

A study by Hsieh (2015) reported CT number differences for a 20 cm water phantom were 1, 1.8, and 2.7 HU at 40, 60, and 80 mm vertical off-centring, respectively [17]. Figure 4 (a) illustrates two ROIs A and B, which are subjected to beam hardening and the bowtie effect. Opposing effects were observed in the upper and lower half of the 20 cm phantom. As the ROI A was vertically off-centred away from the iso-centre, the CT number decreased, while the CT number for ROI B increased as it becomes vertically off-centred towards the iso-centre. The difference in CT number between the two ROIs demonstrated an increase in a factor of two. The difference at 80 mm of off-centring was calculated and divided by two, resulting in the value of 2.75 HU at 120 kVp, which matches the result of Hsieh (2015) at the same distance [17]. This correlates to the principle function of the bowtie filter [32].

Two ROIs were located at both peripheral edges, anteriorly and posteriorly, of the CIRS phantom as shown in Fig. 5 (a). These ROIs demonstrated a larger change in the CT number as a function of vertical off-

centring compared to the values obtained at the phantom centre. This highlights the significance of ROI location on CT number variability. Goodsitt et al. (2006) reported that the CT number is dependent on the ROI location and that the number can change by up to 11 HU for a scanned simulated lung phantom [33]. Szczykutowicz et al. (2016) measured the CT number change in relation to body position and ROI location at a 40, 60, and 100 mm off-centring above and below the gantry iso-centre [34]. They used two ROIs (anterior and posterior) for each scanned area. In the abdominal scan, the mean difference in the CT number compared to the gantry iso-centre was 8 HU obtained at the anterior ROI, and - 6 HU at the posterior ROI with 60 mm off-centre.

In the current study, the mean difference in the CT numbers between the posterior ROI (2), and the anterior ROI (1) was 10.7 HU with 80 mm off-centring at lower tube voltage (80 kVp). This differs from the study by Szczykutowicz et al. who reported a maximum of 19 HU in the abdominal area, at 100 mm vertical off-centring above the iso-centre, asserting that the bowtie influence diminished gradually with vertical off-centring [34]. As a consequence, noise is known to be greater on the phantom side positioned furthest from the gantry iso-centre.

## Tube Voltage

Using the GEMINI GXL system, the Ct number was demonstrated to be energy-dependent. In contrast, as the Siemens system applies an algorithmic correction, the CT number for water energy is independent for the average adult size. However, the CT number was shown to be energy dependent for body tissues other than water.

It emerges clearly that CT numbers are closer in value between 90 and 120 kVp for the GEMINI GXL system. Whereas the Siemens system showed closer values for 110 and 130 kVp when the phantom was off-centred from the gantry iso-centre. This finding reflects the degree of CT number deviation for different scanned body sizes with respect to standard adult size values. In other words, using the lower tube voltage for smaller patient size in the Philips system will result in less CT number deviation as a function of off-centring compared to standard adult values, while this deviation will be higher again using Siemens system and vice versa.

## Limitations

The inability to use the same phantom to examine the performance of each scanner due to COVID-19 restrictions is noted as a limitation, however, the comparison is still applicable since both are water phantoms. The study examined two manufacturers only and further research to include a more comprehensive range of vendors is needed.

## Conclusion

The Siemens system demonstrated acceptable CT number uniformity and energy independence for an adult-sized water phantom at the gantry iso-centre compared to the GEMINI GXL system. As expected,

uniformity and energy dependence were influenced by vertical off-centring. The extent of the change in CT number as a function of vertical off-centring was shown to depend on the degree of the improper alignment of the bowtie filter. The influence was more prominent for the larger phantom size and at lower tube voltages. Furthermore, the CT number deviation was highly dependent on both the size and the location of the measured ROI, and this deviation was observed to be more evident in peripheral phantom areas. Radiologists and radiographers should remain aware of the potential of CT numbers variation associated with poor positioning, especially when there is dependence on CT number accuracy for tissue lesion characterisation. Further research is still needed to support or refute the results of this study.

## Declarations

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## Figures

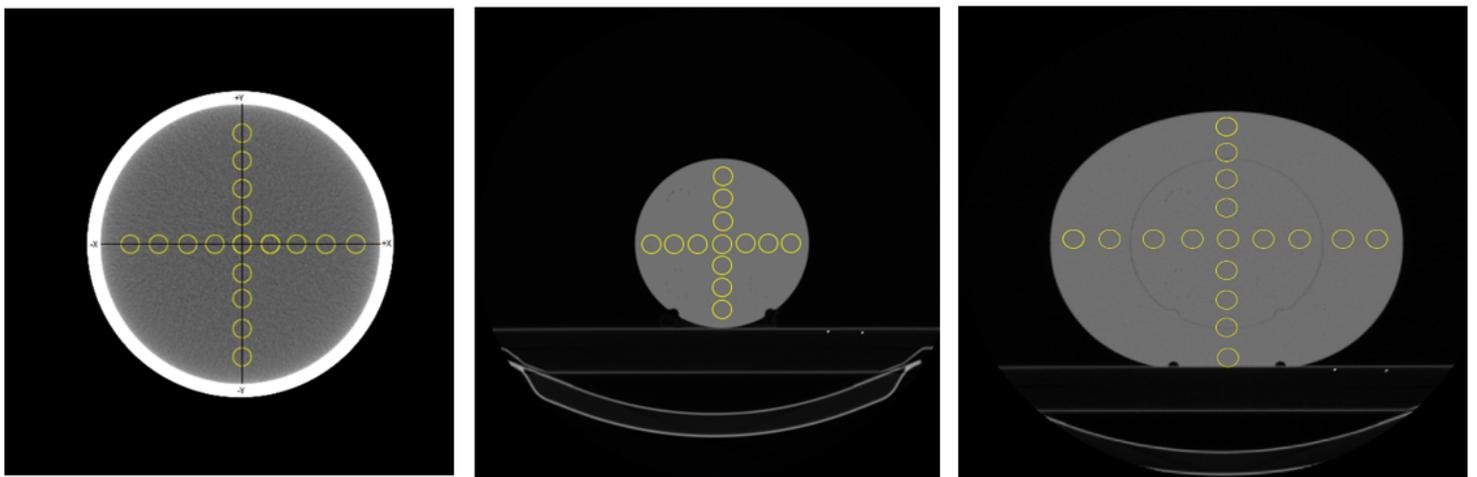
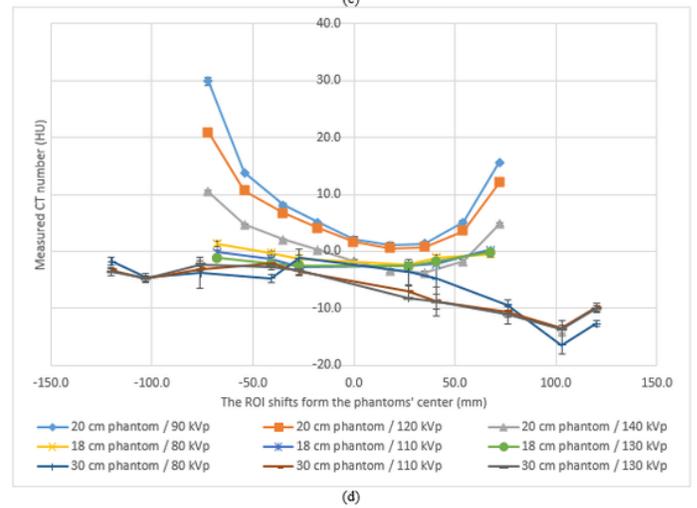
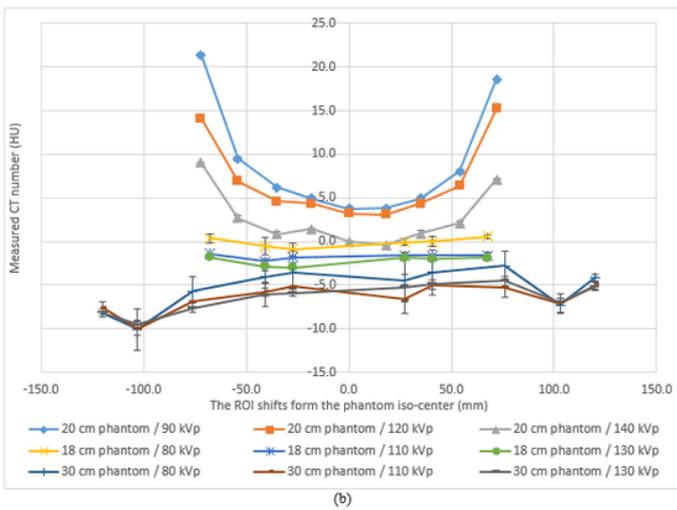
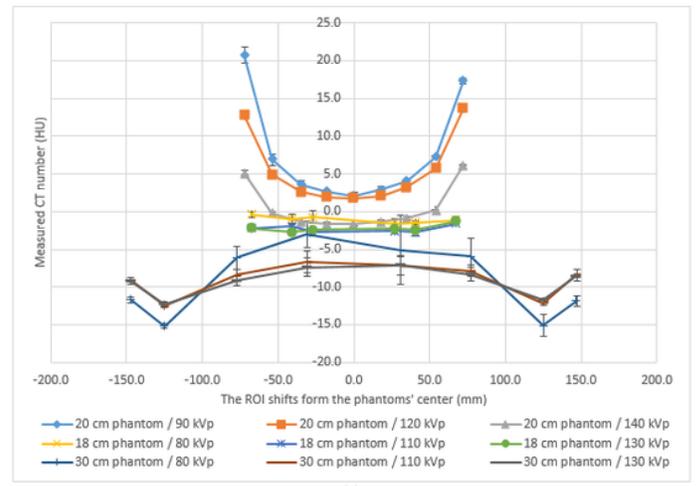
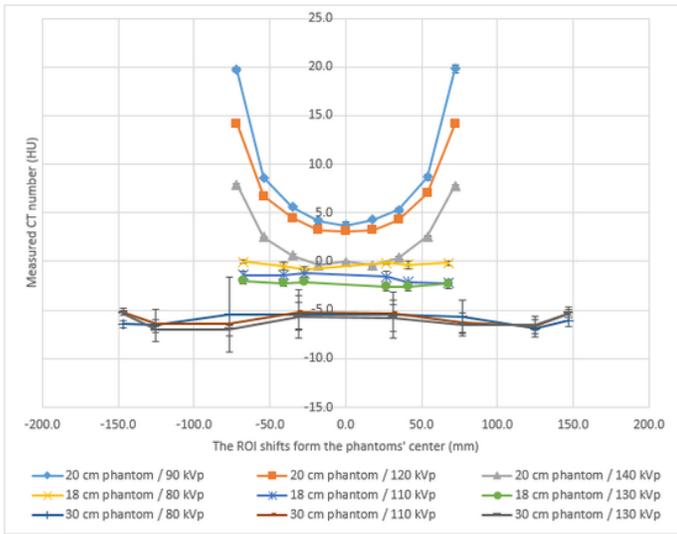


Figure 1

Placement of ROIs across image field (X and Y axis) for uniformity measurements



**Figure 2**

CT number uniformity across X axis at (a) gantry iso-centre and (b) 80 mm off-gantry iso-centre. CT number uniformity across Y axis at (c) gantry iso-centre and (d) 80 mm off-gantry iso-centre for both scanning systems using different tube voltages

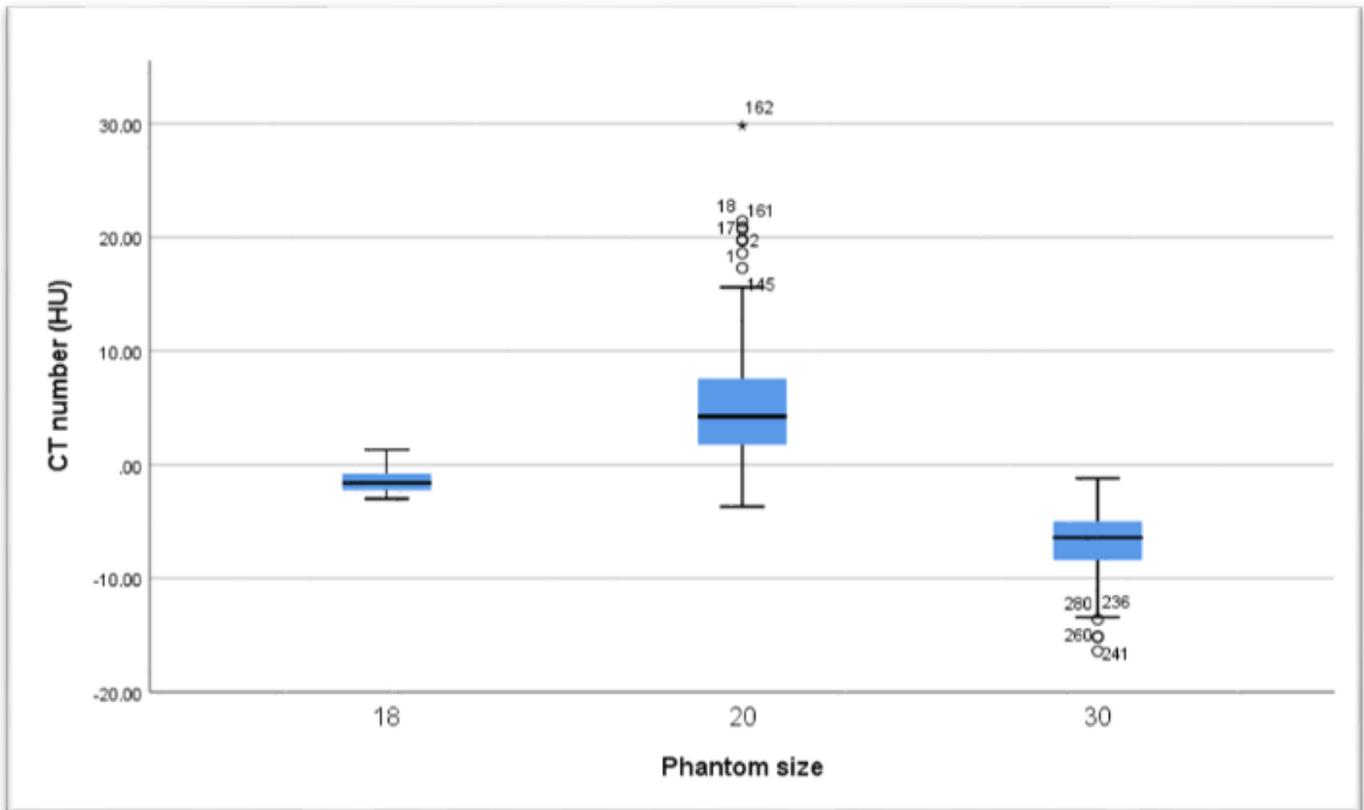
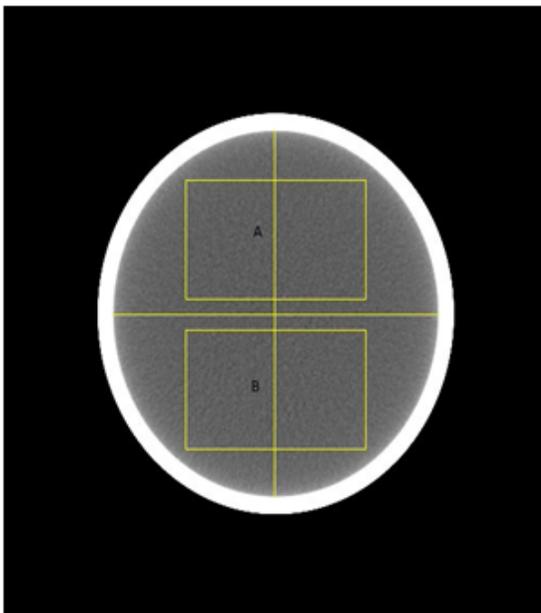
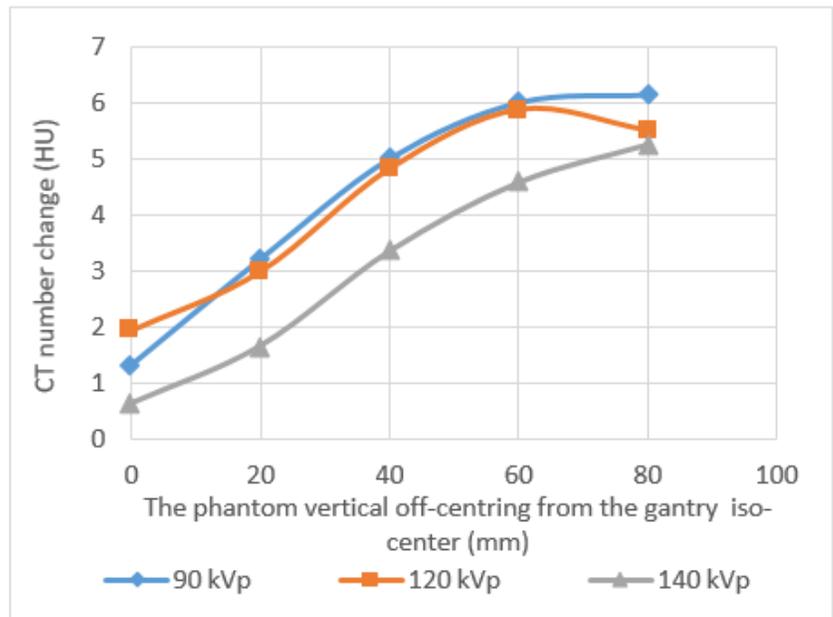


Figure 3

CT number change as a function of the vertical table off-centering for the three phantom sizes



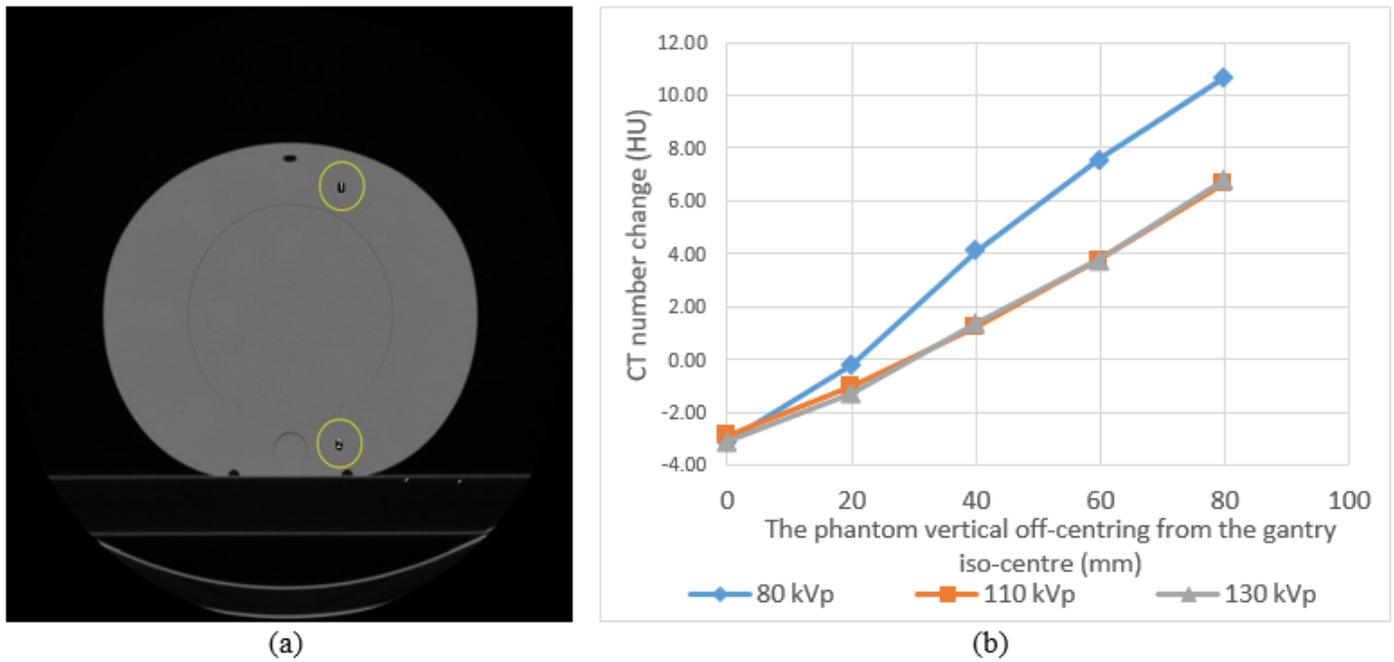
(a)



(b)

Figure 4

(a) Two ROIs defined on the 20 cm water phantom. (b) Graph showing differences between the mean CT number of the lower and the upper ROIs as a function of phantom off-centring using the GEMINI GXL system



**Figure 5**

(a) Two ROIs defined on a CIRS water phantom CT image used for calculating CT number difference. (b) The graph shows differences between mean of the CT number of the upper and the lower ROIs as a function of phantom off-centring using Siemens system