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PHYSICS

Abdominal CT during pregnancy: a phantom study on the effect of patient centring on conceptus radiation dose and image quality

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Abstract
Objectives To investigate the effect of patient centring on conceptus radiation dose and image quality in abdominal CT during pregnancy.
Material and methods Three anthropomorphic phantoms that represent a pregnant woman at the three trimesters of gestation were subjected to a routine abdominal CT. Examinations were performed with fixed mAs (mAs_f) and with the automatic exposure control system (AEC) activated. The percent reduction between mAs_f and modulated mAs (mAs_{mod}) was calculated. Conceptus dose (D_c) was measured using thermoluminencent dosimeters. To study the effect of misplacement of pregnant women on D_c, each phantom was positioned at various locations relative to gantry isocentre. Image quality was evaluated on the basis of image noise, signal-to-noise ratio, and contrast-to-noise ratio.
Results The maximum reduction between mAs_f and mAs_{mod} was 59.8 %, while the corresponding D_C reduction was 59.3 %. D_C was found to decrease by up to 25 % and 7.9 % for phantom locations below and above the isocentre, respectively. Image quality deteriorated when AEC was activated, and it was progressively improved from lower to higher than the isocentre locations.
Conclusion Centring errors do not result in an increase in D_c. To maintain image quality, accurate centring is required.
Key Points
- *AEC activation reduces conceptus radiation dose at all gestational stages.*
- *Patients should be accurately aligned at the gantry isocenter.*
- *Patient centring deserves increased attention in clinical practice.*
- *Pregnant patient centring errors do not considerably affect conceptus dose.*

Keywords Automatic exposure control · Conceptus radiation dose · Vertical miscentring · Horizontal miscentring · Image quality

Abbreviations

CT	Computed tomography
AEC	Automatic exposure control
mAs_f	Fixed mAs
mAs_{mod}	Mean modulated mAs
D_C	Conceptus radiation dose
TLD	Thermoluminesent dosimeters
mAs_{QR}	Quality reference milliampere sec
HU	Hounsfield unit
SD	Standard deviation
ROI	Region of interest
SNR	Signal-to-noise ratio
CNR	Contrast-to-noise ratio

Introduction

Computed tomography (CT) has been an indispensable part of diagnosis in severe abdominal blunt trauma in pregnant patients. CT may also be needed during pregnancy to assess common causes of acute abdominal pain such as suspected appendicitis, bowel obstruction, and pancreatitis especially if other imaging techniques such as ultrasound and magnetic resonance imaging are inconclusive [1–5]. The estimation of conceptus radiation dose is essential to determine radiogenic

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risks to the unborn child and inform the expectant mother [5, 6]. Several studies have been published on conceptus radiation dose from CT examinations during pregnancy [7–13]. For the pregnant patient who needs CT, the most important element is to optimize the examination and keep conceptus radiation dose as low as reasonably achievable.

To optimize patient radiation dose and image quality in CT examinations, manufactures have developed dose reduction tools such as automatic exposure control (AEC) devices [14–19]. These systems adapt the tube current both angularly (x,y-axis modulation) and along the z-axis according to each patient's body size and anatomical characteristics. Several studies have been conducted on the efficiency of AEC systems in reducing patient radiation dose [20, 21]. Considerable reduction in radiation dose has been reported for adult and paediatric patients [20]. Additionally, the use of AEC may be potentially efficient in reducing radiation dose in pregnant patients. No information has been available concerning the effect of AEC on conceptus radiation dose and image quality in pregnant patients referred for CT.

Previous studies have shown that efficient operation of AEC requires accurate alignment of patients at the gantry's isocentre [22–24]. Moreover, several studies have reported that inaccurate patient centring at the gantry's isocentre affects the pattern of the radiation dose delivered to the radiosensitive organs of the human body [25–27]. Li et al has shown that 97 % of examined patients are not correctly centred [28]. Inaccurate alignment might be more frequent in pregnant patients than in the rest of the examined population due to the increased size and the oval shape of the maternal abdomen. The question which arises is whether the misplacement of a pregnant patient in AEC-activated abdomen and pelvis CT examinations affects conceptus radiation dose. A potential increase in conceptus dose owing to patient misplacement might raise concern especially in high dose examinations. This effect should thus be taken into account on the estimation of conceptus radiation dose and the assessment of risk versus benefit for mother and unborn child. However, to our knowledge the influence of patient miscentring on conceptus dose in AEC-activated abdomen and pelvis CT examinations has not been investigated yet. In addition, existing studies performed in adult, non-pregnant individuals are limited to investigating only the vertical off-centring when AEC is activated. However, the horizontal off-centring is expected to be different from that of vertical off-centring [29].

The aim of this study was to:

i) assess the effect of AEC system on conceptus radiation dose and image quality using phantoms simulating pregnancy during the three trimesters of gestation.
ii) investigate the effect of horizontal and vertical misplacement of pregnant patients on conceptus radiation dose and image quality.

Materials and methods

Anthropomorphic phantoms

A modified adult anthropomorphic Rando phantom (Alderson Research Labs, Stanford, CA, USA) was used for the conceptus radiation dose measurements. The Rando phantom consists of 36 numbered 2.5-cm thick contiguous slabs, which are made of radiologically tissue-equivalent material. This phantom simulates an average person of 1.73 m height and 73.5 kg weight and has been widely used for conceptus radiation dose measurements during the first postconception weeks and the first trimester of gestation. In this trimester the abdominal dimensions are not considerably increased due to the growth of the conceptus. To simulate pregnancy at the second and third trimesters, 2.5-cm thick rings made of Lucite were added. Seven rings were added around the slices 25 to 31 to simulate a pregnant woman during the second trimester, whereas ten rings were added to slices 22 to 31 to simulate pregnancy in the third trimester. Phantom slices and Lucite rings contain several holes, which allow the placement of thermoluminescent dosimeter (TLD) crystals. Figure 1a shows the Rando phantom simulating pregnancy at the 2nd trimester of gestation. Detailed description of the phantoms simulating pregnancy can be found elsewhere [7].

CT system and automatic exposure control mechanism

All CT acquisitions were performed using a 16-slice CT system (Sensation 16, Siemens, Germany) equipped with a combined z-axis and angular (x, y)-based automatic exposure control system (AEC). Information on the operation characteristics of this tube current modulation system has been published previously [14–16]. In this study, AEC was accomplished by means of the CARE Dose 4D algorithm (software version syngo CT 2006G, Siemens, Erlangen, Germany). An image quality reference milliampere sec (mAs_{QR}) value was predefined for every scan protocol. The AEC software allows the use of different modulation strengths for slim and obese patients. By default, the modulation strength is set by the manufacturer to the "average decrease" for slim and "average increase" for obese patients. Being the default, this setting is expected to be followed in the everyday clinical practice by most institutions. Table 1 lists the values of the exposure and image reconstruction parameters which were used.

To investigate the potential of AEC in reducing conceptus radiation dose, the phantoms simulating pregnancy at the first, second, and third trimesters of gestation were scanned using a routine abdominal examination protocol. CT acquisitions were first performed with fixed tube current and then with the AEC activated. The borders of abdominal CTs were extended from the dome of the diaphragm down to the pubic symphysis. The percent differences between fixed and mean

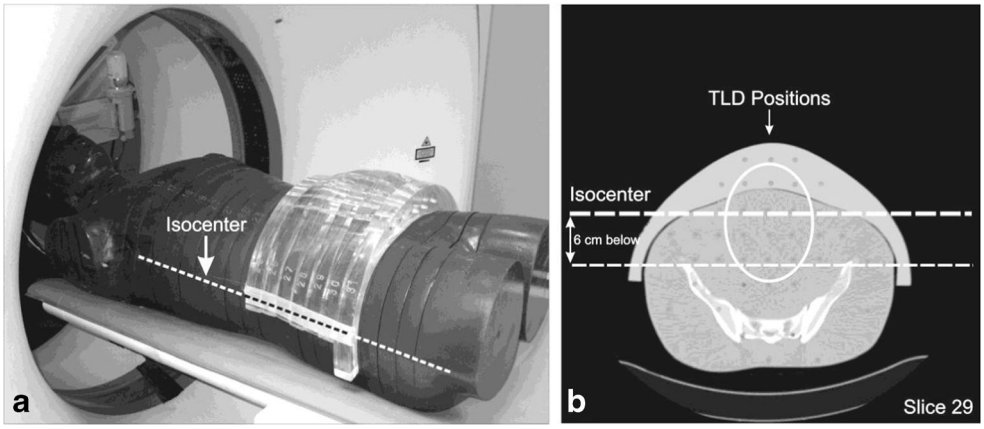


Fig. 1 (a) the phantom simulating pregnancy at the 2nd trimester of gestation. The phantom is accurately aligned at the gantry's isocentre (*white dashed line*); (b) an axial image (slice 29) of the phantom positioned 6 cm below the gantry isocentre. The TLD crystal positions selected for conceptus dose measurements at this slice are within the elliptical outline.

modulated tube current time product, which was obtained from the DICOM header of the image slices depicting conceptus at each trimester and between conceptus radiation dose with and without AEC activation, were calculated as follows:

$$\%mAs_{reduction} = \left(\frac{mAs_f - mAs_{\mathrm{mod}}}{mAs_f}\right) \times 100 \quad (1)$$

where mAs_f and mAs_{mod} are the fix and mean modulated tube current time product, respectively.

The corresponding percent conceptus radiation dose difference (% D_{con}) achieved by AEC activation was calculated using the following equation:

$$\%D_c = \left(\frac{D_C^{FIX} - D_C^{AEC}}{D_C^{FIX}}\right) \times 100 \quad (2)$$

where D_C^{FIX} and D_C^{AEC} are the conceptus radiation dose values estimated for fixed tube current and AEC-activated scans, respectively.

To study the effect of inaccurate alignment of pregnant patients on conceptus radiation dose and image quality, the three phantoms were placed in various locations relative to the gantry isocentre. In particular, to investigate the patient centring along the vertical axis each phantom was placed in five different positions: isocentre, 3 cm below, 6 cm below, 3 cm above, and 6 cm above gantry isocentre. Figure 1b shows an axial image of the phantom at the 2nd trimester positioned 6 cm below the gantry isocentre. Moreover, to investigate the horizontal off-centring, each phantom was placed 2.5 cm right, 4.5 cm right, 2.5 cm left, and 4.5 cm left from the gantry isocentre.

To obtain a detectable signal and reduce statistical errors of radiation dose measurements, three identical scans were carried out for each position of each phantom.

Conceptus radiation dose measurements

Lithium fluoride (TLD-100) (Harshaw, OH) chips, 3 x 3 x 0.9 mm, were used to measure the radiation dose absorbed by the conceptus. Two TLD chips were used at each measuring position. TLDs were placed in various depths within the phantom simulating pregnancy during the first trimester. Specifically, 12 TLDs were loaded along the midline of slices 29 and 30, in holes located 5.5 cm, 8.5 cm, and 11.5 cm from the anterior surface of the Rando phantom. Conceptus radiation dose was calculated as the mean value averaged over the dose measured by the 12 TLD crystals. One hundred and twenty-two and 214 TLDs were loaded at slices 25 to 31 and 22 to 31 of the phantom simulating the second and third trimesters of pregnancy, respectively. The TLD crystal positions selected for conceptus dose measurements at slice 29 of the phantom simulating pregnancy at the 2nd trimester of gestation are within the elliptical outline shown in Fig. 1b. The conceptus absorbed dose (D_C) was then calculated as follows:

$$D_C = \sum_{i=1}^{m} f_i + \left(\frac{1}{n}\sum_{j=1}^{n} D_j\right) \quad (3)$$

where m is the total number of phantom slices containing the conceptus in the second or third trimester, f_i the volume fraction of the conceptus contained in each consecutive slice, n is the total number of TLD chips per phantom slice, which are located within conceptus, and D_j is the dose measured by the TLD crystal.

To calibrate TLD signal, a conventional x-ray tube was used. The calibration was performed at 120 kVp using the Barracuda x-ray multimetre (RTI Electronics, Mölndal, Sweden). Sheets of aluminum of appropriate thicknesses were attached at the output of the radiologic tube to simulate the half-value layer of the CT system. The reading of irradiated TLDs was performed using a Harshaw-3500 reader (Thermo-

Fisher Scientific, MA, USA). The calibration coefficient (CF) of each TLD was determined as follows:

$$CF_j = \frac{D_{air}}{TLD_j^{Signal}} \quad (4)$$

where D_{air} is the known dose in the air and TLD_j^{Signal} is the TLD signal measured by the jth TLD. To increase accuracy, TLD crystals were grouped, according to recorded signal. The standard error of each group was less than 3 %. The TLD signal measured by the jth TLD was converted to an absorbed dose (D_j) using the following equation:

$$D_j = \left[\frac{\left(\frac{\mu_{en}}{\rho}\right)_j}{\left(\frac{\mu_{en}}{\rho}\right)_{air}}\right] \times (CF) \times \left(TLD_j^{Signal}\right) \quad (5)$$

where, $(\mu_{en}/\rho)_j$ is the mass energy absorption coefficient of soft tissue and $(\mu_{en}/\rho)_{air}$ the mass energy absorption coefficient of air. Before each measurement, TLD-100 crystals were annealed at 400 °C for 1 h followed by 20 h at 80 °C using a TLD annealing oven (Victoreen Inc., OH, USA).

Image quality assessment

To evaluate the effect of AEC on image quality, images obtained from fixed tube current CT acquisitions were compared to the corresponding images obtained from AEC-activated scans. Moreover, to assess the effect of miscentring on image quality, images derived from CT scans performed at isocentre, were compared to the corresponding images obtained with the phantom placed at various locations along x- and y-axes. The comparison was based on image noise, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) measurements. These measurements were performed in images depicting conceptus at each trimester. Image noise was defined as the standard deviation (SD) of the mean Hounsfield unit (HU) value in circular regions of interest (ROI, 2 cm^2). These ROIs were drawn over uniform soft-tissue equivalent image areas. SNR was calculated as the ratio of the mean HU pixel value within a ROI to SD. CNR was calculated as the ratio of the absolute mean difference between mean HU pixel value within the above ROI and mean HU pixel value within a ROI of the same size in the air, divided by the SD.

Five ROIs were drawn at image slices obtained from fixed tube current CT acquisitions. These ROIs were copied at exactly the same anatomic locations in the corresponding images obtained from AEC-activated CT acquisitions. The same procedure was followed to evaluate the effect of off-centring on image quality. Five ROIs were drawn at the images derived from scans performed in the following positions: isocentre, 3 cm and 6 cm below isocentre, 3 cm and 6 cm above isocentre, 2.5 cm and 4.5 cm right from isocentre, and 2.5 cm and 4.5 cm left from isocentre. Quantitative image analysis was performed using the ImageJ image analysis software (version 1.42q, Java, NIH, Bethesda, MD, USA).

Results on SNR and CNR were expressed as means± standard deviations. To compare image noise, SNR and CNR values between fixed tube current and AEC-activated acquisitions, the Student's *t* test for paired samples was used. To compare these image quality parameters between phantom CT scans at the isocentre and at various locations along x- and y-axes, the one-way analysis of variance (ANOVA) test was used. A significant difference was set at a p value of less than 0.05. All statistical analyses were performed using the MedCalc software package (MedCalc software, version 13, Mariakerke, Belgium).

Results

Figure 2 illustrates the mAs(z) profiles derived from a routine abdominal CT acquisition of the phantoms simulating pregnancy at the first, second, and third trimesters of gestation. These profiles were obtained with the phantoms aligned at the gantry's isocentre. It is obvious that in all stages of gestation, the modulated mAs(z) profile values are considerably lower than the fixed mAs value shown with the horizontal line. In the abdominal region depicting conceptus, the mean mAs_{mod} value was decreased compared to the fixed mAs level by 59.8 %, 49.3 %, and 47.0 % for the first, second, and third trimesters respectively.

The data presented in Fig. 3 show the conceptus radiation dose at each trimester of gestation from CT acquisitions performed with fixed tube current and with the AEC activated. The percent difference in conceptus radiation dose was found to be 59.3 %, 54.8 %, and 48.7 % at the first, second, and third trimesters, respectively.

The comparison of image noise values between the images obtained from the fixed tube current CT acquisitions and the corresponding images obtained from AEC-activated scans is shown in Fig. 4. Image noise was found to increase significantly when AEC was activated ($p<0.001$). Moreover, image noise was found to increase with gestational stage. The SNR and CNR values, listed in Table 2, were found to decrease significantly when AEC was activated ($p<0.005$). In addition, SNR and CNR values decreased as gestational age increased.

The effect of off-centring on conceptus radiation dose and image noise is summarized in Fig. 5. Figure 5a shows the conceptus radiation dose and mAs_{mod} as a function of the phantom's positions along the vertical axis. mAs_{mod} increased

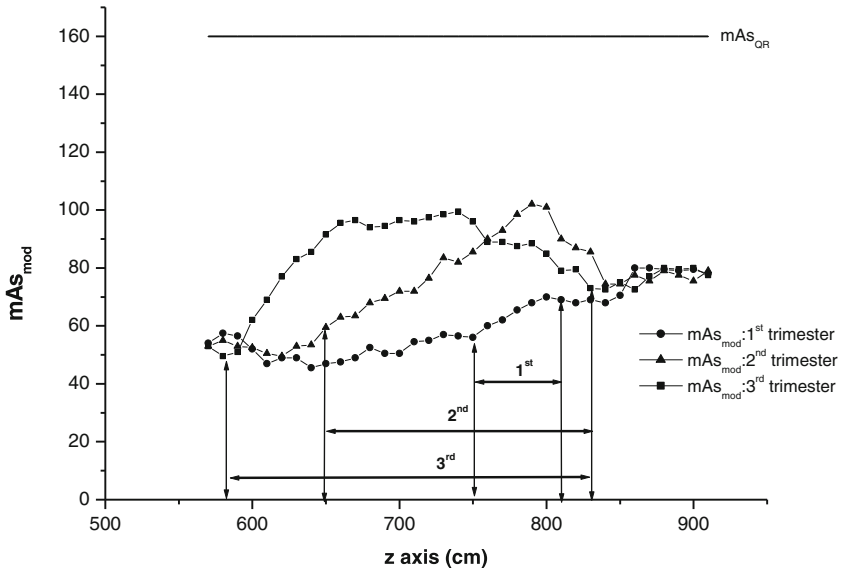


Fig. 2 mAs(z) profile curves recorded in the abdominal region of phantoms simulating pregnancy at first, second, third trimesters of gestation. The mAs_f level is shown with the *horizontal line*. Vertical lines define the spatial extent of conceptus along the z-axis at each trimester.

with the phantom's positions along vertical axis. From 6 below to 6 cm above the gantry isocentre, mAs_{mod} increased from 48.2 mAs to 81.5 mAs, 62.5 mAs to 99.3 mAs, and 77.8 mAs to 99.1 mAs, for the first, second, and third trimesters, respectively. When the phantom was aligned at the isocentre (0 cm), the conceptus radiation was 7.2 mGy, 7.6 mGy, and 7.7 mGy at the first, second, and third trimesters, respectively. The conceptus radiation dose was decreased for phantom locations below the isocentre for all trimesters. Specifically, at 6 cm below the gantry isocentre, conceptus radiation dose was 5.4 mGy, 5.7 mGy, and 5.9 mGy for the first, second, and third trimesters, respectively. On the contrary, a slight decrease in conceptus radiation dose was observed as the phantom was elevated above the isocentre. At 3 cm above the gantry isocentre, conceptus radiation dose was 7.2 mGy, 7.5 mGy, and 7.6 mGy at the first, second, and third trimesters, while at 6 cm above the gantry isocentre, the corresponding values were 7.0 mGy, 7.0 mGy, and 7.1 mGy, respectively.

Figure 5b illustrates the conceptus radiation dose and mAs_{mod} when the phantom was placed at various positions along the horizontal axis. From 4.5 cm right to the isocentre, mAs_{mod} values ranged from 70.2 mAs to 64.4 mAs for the first trimester. The corresponding change for the second and third trimesters was not considerable (Fig. 5b). Conceptus radiation dose was not substantially altered when the phantoms were placed in various positions along the horizontal

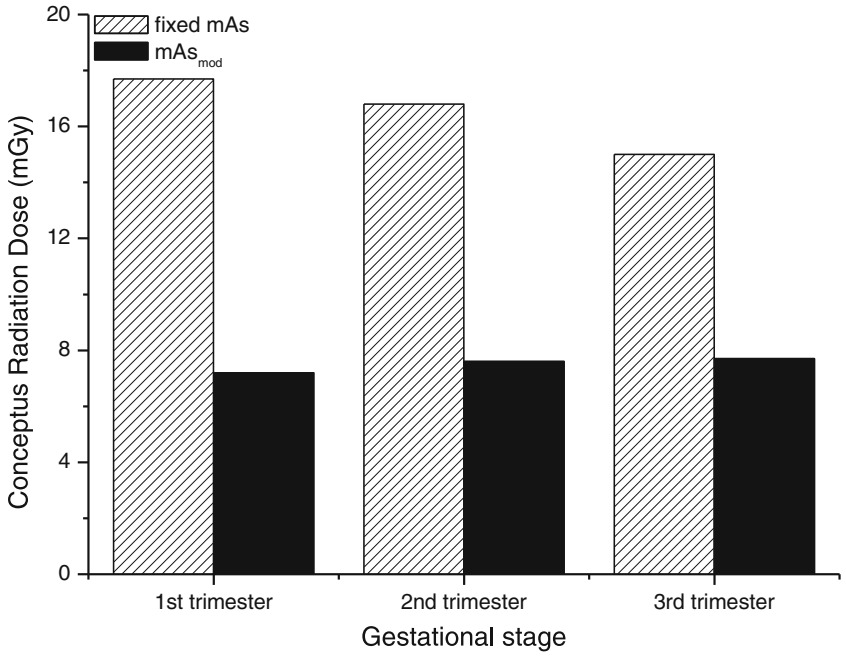


Fig. 3 Conceptus radiation dose at each trimester of gestation from CT scans performed with fixed tube current and with the AEC activated.

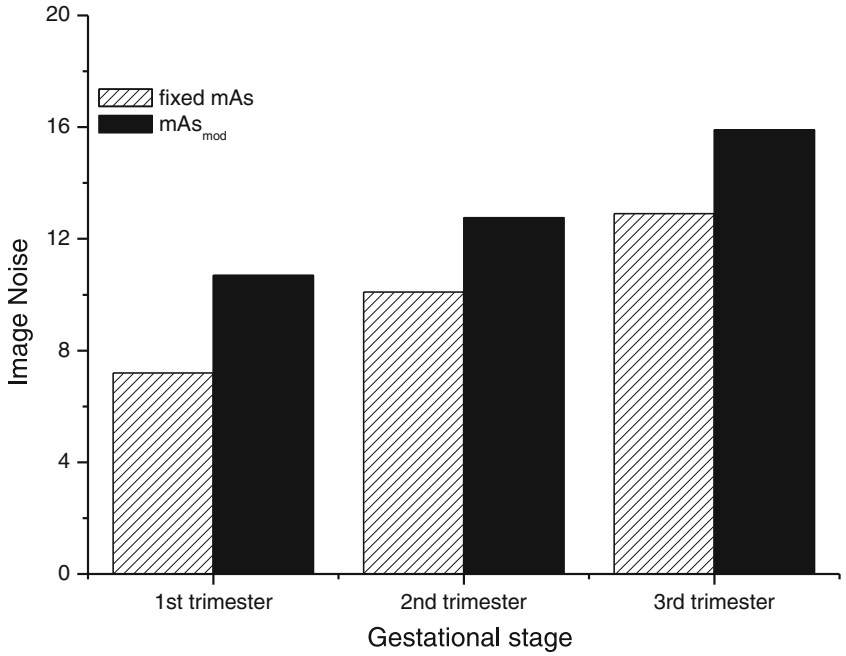


Fig. 4 Image noise values obtained with fixed tube current and AEC-activated CT scans at each trimester. Images were obtained with the phantom placed at isocentre.

axis. A maximum difference of approximately 9 % was recorded in the phantom simulating the first trimester of gestation at the horizontal position of 4.5 cm relative to the gantry isocentre.

Figure 5c, d illustrates the image noise values derived from vertical and horizontal off-centring experiments, respectively. For all stages of gestation, image noise was progressively decreased from lower to higher than that recorded at the isocentre location ($p<0.001$). On the contrary, image noise was not significantly modified with different phantom positions in horizontal direction relative to the gantry isocentre ($p>0.1$).

Tables 3 and 4 list SNR and CNR values, which were derived from measurements on CT images from vertical and horizontal off-centring, respectively. SNR and CNR values were progressively increased from lower to higher than those recorded at isocentre locations (Table 3), for all stages of gestation ($p<0.001$). Typically, 6 cm above gantry isocentre, SNR and CNR were increased by 9.6 % and 13.2 % at the first, 9.6 % and 7.9 % at the second, and 13.4 % and 8.5 % at the third trimesters of gestation, respectively. SNR was not significantly modified with different phantom positions in horizontal direction relative to the gantry isocentre in the first trimester of gestation ($p>0.05$). On the contrary SNR values were significantly reduced at the second and third trimesters ($p<0.001$). The corresponding CNR values were significantly modified at the first trimester of gestation ($p<0.001$) while not substantially altered at the second and third trimesters ($p>0.1$).

Table 1 Exposure and image reconstruction parameters

Parameter	
kVp	120
Fixed mAs (mAs_f)/Image Quality Reference (mAs_{QR})	160/160
Gantry cycle (s)	0.5
Pitch	0.75
Detector Configuration (mm)	16×1.5
Section Thickness (mm)	10
Reconstruction Kernel	B30f
Scan Field of View (cm)	50
Topogram	Anterior–Posterior
Modulation Strength	Average decrease–average increase

Discussion

In pregnant patients who undergo CT, maternal and conceptus radiation dose should be kept as low as reasonably achievable. One of the techniques adopted in an attempt to reduce patient radiation dose is AEC [15–19]. Although several studies have reported data on the efficiency of AEC systems in optimizing patient radiation dose and image quality [22–24], review of the literature reveals lack of information regarding the effect of AEC systems on conceptus radiation dose and image quality when pregnant patients undergo AEC-activated CT imaging. The data presented in this study indicate that conceptus radiation dose may be considerably reduced when the AEC system is activated, even at the third trimester of gestation when the abdomen has reached its maximum size. Moreover, the improper alignment of the pregnant patient at the

Table 2 SNR and CNR values obtained with fixed tube current and AEC-activated CT scans at each trimester. These values were obtained with the phantoms placed at isocentre.

	1st Trimester		2nd Trimester		3rd Trimester	
	CNR	SNR	CNR	SNR	CNR	SNR
Fixed mA	140.43±2.00	1.82±0.12	100.00±1.49	1.20±0.05	78.27±1.14	0.90±0.04
AEC	91.88±1.38	1.43±0.09	79.81±1.15	1.05±0.03	63.68±1.00	0.789±0.03

gantry isocentre does not influence considerably conceptus radiation dose. However, the results of the current study illustrate that improper alignment may deteriorate image quality. Thus, to maintain image quality, accurate centring is required.

This study indicates that the mAs_{mod} values were decreased compared to the mAs_f by up to 59.8 %. Conceptus radiation doses measured in AEC activated CT acquisitions were lower compared to the corresponding values obtained without the AEC activation with a maximum percentage dose reduction at 59.3 %. A recent study performed to estimate conceptus radiation dose in patients undergoing abdominal CT in the first 7 weeks of gestation, reported a mean mAs reduction of 52 % and a conceptus radiation dose reduction of 50.2 % [9].

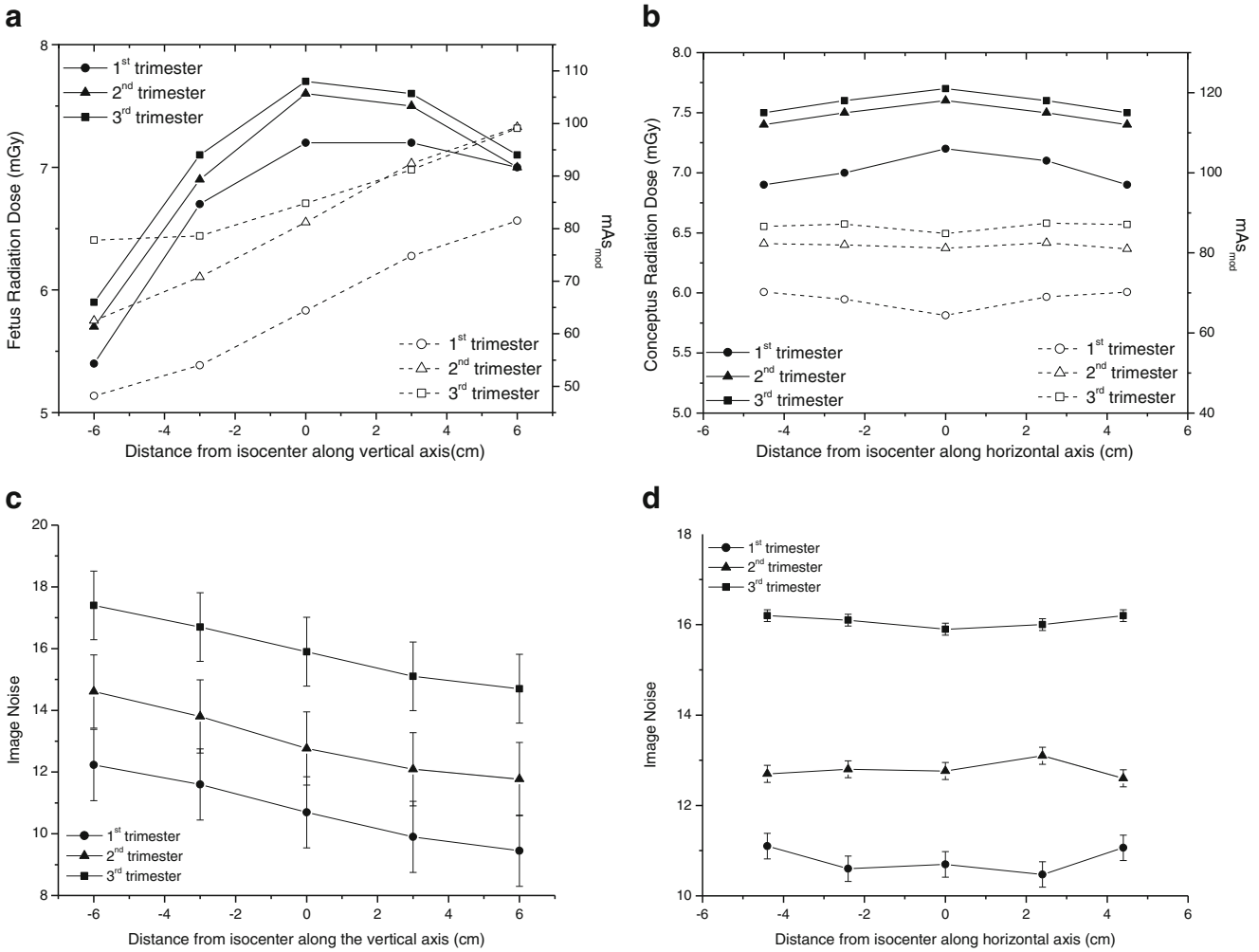


Fig. 5 (*a*) Conceptus radiation dose and mAs_{mod} as a function of the vertical distance from isocentre. mAs_{mod} was calculated as the mean tube current-time product in the image slices depicting conceptus. *Positive* and *negative numbers* indicate the phantom positions above and below the gantry isocentre, respectively. (*b*) Conceptus radiation dose and mAs_{mod} as a function of the horizontal distance from isocentre. mAs_{mod} was calculated as the mean tube current-time product in the image slices depicting conceptus. *Positive* and *negative numbers* indicate the phantom positions right and left relative to the gantry isocentre, respectively. (*c*) Image noise as a function of the vertical distance from isocentre. *Error bars* represent 2 x SD. *Positive* and *negative numbers* indicate the phantom positions above and below the gantry isocentre, respectively. (*d*) Image noise as a function of the horizontal distance from isocentre. *Error bars* represent 2 x SD. *Positive* and *negative numbers* indicate the phantom positions right and left relative to the gantry isocentre, respectively.

Table 3 SNR and CNR values obtained from CTs performed with the phantoms placed in various locations along vertical axis

Distance along vertical axis (cm)	1st Trimester		2nd Trimester		3rd Trimester	
	CNR	SNR	CNR	SNR	CNR	SNR
−6	80.71±1.16	1.025±0.069	69.34±1.17	0.821±0.056	58.04±0.10	0.680±0.061
−3	84.91±1.32	1.155±0.077	73.73±1.11	0.975±0.052	60.53±0.91	0.771±0.037
0	91.88±1.38	1.429±0.093	79.81±1.15	1.053±0.033	63.68±1.00	0.789±0.034
3	99.33±1.60	1.625±0.104	84.04±1.30	1.257±0.063	66.73±1.07	0.967±0.049
6	104.00±1.56	1.566±0.098	86.08±1.51	1.154±0.099	69.07±1.21	0.899±0.069

These findings are in close agreement to the abovementioned data of the current study for the first trimester of gestation.

Several studies have been published on the effect of patient centring on radiation dose and image noise in AEC activated CT examinations of non-pregnant individuals. These studies have shown that tube current or image noise may increase when patients are not correctly aligned at the gantry isocentre [24, 25, 29]. A clinical study performed in non pregnant individuals by Li et al., indicated that it is common for CT operators to position patients below the gantry isocentre [28]. The mean miscentring distance recorded was 3.3 cm. In the same study, surface and peripheral radiation dose were found to increase by up to 50 % when the patient is centred 6 cm below the gantry isocentre [28]. The above studies have investigated the effect of vertical off-centring of non-pregnant individuals on radiation dose to the skin and organs located to peripheral portions of the patient's trunk. The effect of vertical off-centring on radiation dose in organs located in the central portion of patient's body, such as the growing conceptus in the mother's body, is not known. The current phantom study provided dosimetric data about conceptus radiation dose when the maternal body at three stages of gestation was intentionally placed off-centre at various locations relative to the isocentre. In particular, when phantoms were vertically off-centred below the gantry isocentre, a decrease in conceptus radiation dose was observed in all trimesters. This effect may be attributed to the following reasons. First, the positioning of the phantom below the gantry isocentre reduces the size of the phantom's body, which is imaged on the topogram. As a result, the AEC system, which controls tube current based on patient's body size imaged on the topogram, reduces the mAs_{mod} and consequently conceptus radiation dose. Second, the positioning of the phantom below the gantry isocentre causes a misalignment relative to the bow-tie filter. This misalignment results in a reduction of the x-ray beam intensity in the central portions of the body cross section, and therefore, a reduction on conceptus radiation dose [25, 26]. On the contrary, no substantial change in conceptus radiation dose was observed when the phantom was elevated 3 cm above the isocentre. However, a further phantom elevation at 6 cm was associated with a slight reduction in conceptus radiation dose. Although mAs_{mod} increases for phantom positions above the gantry isocentre due to the increased body size imaged on the topogram, conceptus radiation dose is reduced. This implies that a potential conceptus radiation dose increase due to the increase in mAs_{mod} is compensated by the reduction in the x-ray beam intensity at the central portion of the body cross section owing to the phantom misalignment relative to the bow-tie filter. The data presented in the current study show that when the phantoms are placed in various positions along the horizontal axis, conceptus radiation dose is not substantially altered (Fig. 5b). When the phantom was positioned 4.5 cm right or 4.5 cm left from the isocentre, a slight phantom elevation was provoked. This is due to the narrow and curved shape of the patient's table top. Thus, a slight magnification of the phantom's body, imaged on the topogram, compared to that at the isocentre was induced. As a consequence, the mAs_{mod} was

Table 4 SNR and CNR values obtained from CTs performed with the phantoms placed in various locations along horizontal axis

Distance along horizontal axis (cm)	1st Trimester		2nd Trimester		3rd Trimester	
	CNR	SNR	CNR	SNR	CNR	SNR
−4.5	88.58±1.29	1.506±0.086	79.48±1.12	0.800±0.065	62.36±0.88	0.625±0.042
−2.5	92.79±1.61	1.414±0.102	79.29±1.33	0.958±0.056	62.83±1.06	0.721±0.045
0	91.88±1.38	1.429±0.093	79.81±1.15	1.053±0.031	63.68±1.00	0.789±0.034
2.5	96.81±1.46	1.426±0.090	78.35±1.25	0.870±0.064	63.17±1.16	0.751±0.051
4.5	91.82±1.59	1.540±0.091	79.82±1.40	0.840±0.097	62.32±1.09	0.614±0.056

slightly increased. However, this increase did not substantially alter conceptus radiation dose due to the subsequent phantom misalignment relative to the bow-tie filter.

It should be noted that when the AEC system investigated in this study is activated, image quality is not preserved among patients of different body size. Specifically, a recent study performed on the same Siemens CT scanner, has shown a 32 % image noise increase in the abdominal region of obese compared to average adults [30]. Other manufacturers have adopted different approaches for AEC. They aim to reach a specified image quality level at any patient size by predefining this level using a 'noise index' (GE Healthcare), a 'reference image' (Philips), or a 'standard deviation of CT numbers' (Toshiba). As a result, a higher radiation dose delivered to patients with large body size, such as pregnant patients at the 2nd and 3rd trimesters of gestation, is expected. However, the assessment of pregnant patients' off-centring on conceptus radiation dose using AEC systems made by the mentioned manufacturers is not known. Further studies are needed to investigate the effect of off-centring on conceptus dose when the AEC system is activated in CT systems of other vendors.

The present study demonstrates that the image noise is significantly modified when the AEC is activated ($p<0.001$). This finding is in agreement with previous studies which have investigated the effect of AEC on image noise [20, 21, 31, 32]. In addition, SNR and CNR values were decreased by up to 21 % and 34 %, respectively. The acquisition of images of diagnostic quality is of paramount importance to ensure that all significant accessory findings are detected. Further in vivo studies are needed to examine whether the reduced image quality originated from AEC activation still offers reliable diagnosis in everyday clinical practice.

Image noise was found to increase progressively from higher to lower than the isocentre locations for all stages of gestation. When the phantom is positioned below the gantry's isocenter, the reduction of mAs_{mod} and the misalignment relative to the bow-tie filter result in higher image noise. Previous studies have shown that off-centering along the vertical axis of the gantry alters [24, 29] image noise. Up to 30 % was the maximum increase in image noise, which was recorded in phantom positions 6 cm below the gantry isocenter [24]. SNR and CNR values were found to decrease from higher to lower than the isocenter locations, for all stages of gestation.

The results of the current study suggest that the impact of patient centering on dose and image noise deserves increased attention in clinical practice. To optimize image quality at the minimum possible radiation dose patients should be accurately aligned at the gantry isocentre. Several studies have, however, shown that in routine clinical practice of CT imaging it is common for patients to be inacurately positioned. Toth et al. found that almost half of the patients enrolled were off-centre with a mean off-centring of 2.3 cm below the gantry isocenter. Li et al. found that almost 95 % of the patients were off-centere with a mean off-centering distance of about 3.3 cm, while 97 % of them were centered below the gantry isocenter [28]. These findings have indicated that vertical off-centering, especially below the gantry isocentre, is most frequent. The current study showed that a possible miscentering of the pregnant patient below the gantry isocenter does not increase conceptus radiation dose but deteriorates image quality. In particular, image noise was increased by up to 14.5 % while SNR and CNR values were decreased by up to 28 % and 13 %, respectively, when phantoms were located 6 cm below the gantry isocenter. Thus, to ensure optimal image quality and avoid loss of significant accesory findings, pregnant patients have to be exceptionally centered at the gantry isocentre. On the contrary, a possible miscentring of the pregnant patient few centimeters (3 cm) above the gantry isocenter delivers roughly the same radiation dose to the conceptus compared to that at the isocenter with improved image quality. Several methods have been reported on the estimation of conceptus radiation dose in pregnant patients who are refered for CT examinations [7–13]. In these methods, pregnant patients are assumed to be correctly positioned at the isocenter. However, as already mentioned, small patient centring errors may not be avoided in the clinical practice. The results of this study indicate that in these cases conceptus radiation dose is not considerably affected. Thus, even in cases where the maternal body is not accurately aligned at the gantry's isocentre these methods can still be used to estimate conceptus radiation dose.

This work has its limitations. All measurements were performed using phantoms representing the average pregnant patient at three trimesters of gestation. The results documented herein may potentially vary in the routine clinical practice when pregnant patients with varying body size and anatomy are examined. However, direct measurements on conceptuses are not feasible. Another limitation is that image quality could not be assessed clinically in the current phantom study. Further studies should be performed on a cohort of pregnant patients to investigate at what extent the image quality delivered by the AEC activated CT acquisitions is clinically acceptable. The main purpose of this study was to investigate whether off-centre positions affect conceptus radiation dose in AEC-activated acquisitions. Thus, the degree of overexposure of the mother with off-centre positions has not been investigated in the current study. However, the effect of miscentring on patient's exposure is not expected to be different between pregnant and non-pregnant individuals. Moreover, the experiments were performed using only one type of CT scanner. It would be interesting to perform similar evaluations in CT scanners with multi-detectors having wider z-axis coverage and with other types of AEC systems.

In conclusion, the activation of AEC system reduces conceptus radiation dose at all gestational stages. Although, pregnant patient-centring errors do not considerably affect

conceptus dose, CT operators should realize the importance of correct patient centring at the gantry isocentre to provide images that meet specific diagnostic tasks at the minimum possible radiation burden.

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