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Fetal Dose from Positron Emission Tomography and Computed Tomography in Pregnant Patients

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Abstract

In cases where pregnancy is discovered during or after a diagnostic examination, the physician or the patient may request an estimate of the radiation dose received by the fetus as per guidelines and standard operating procedures (SOPs). This study provides the imaging community with dose estimates to the fetus in PET/CT with protocols that are adapted to low dose protocols for patients known to be pregnant from the University of Michigan. There were nine patients analyzed with data for the first, second and third trimester, the availability of which is quite rare. These images were used to calculate the size-specific dose estimate (SSDE) from the CT scan portion, and the standard uptake value (SUV) and ^{18}F-FDG uptake dose from the PET scan portion using the Medical Internal Radiation Dose (MIRD) formulation. The fetal dose estimates were tested for correlation with each of the following independent measures: gestational age, fetal volume, average water-equivalent diameter of the patient along the length of the fetus, size-specific dose estimate (SSDE), SUV, percentage of dose from FDG . Stepwise multiple linear regression analysis was performed to assess the partial correlation of each variable. This is the first study where fetal doses have been determined from CT and PET images. Fetal self-doses from ^{18}F for the 1st, 2nd and 3rd trimester range from 2.18 mGy (single data point), 0.74-1.82 mGy and 0.017-0.0017 mGy. The combined SSDE and fetal self dose ranges from 1.2-8.2 mGy. These types of images from pregnant patients are rare. Our data indicate that the fetal radiation exposure from ^{18}F-FDG PET and CT performed, when medically necessary, in pregnant women with cancer is low. All efforts should be made to minimize the fetal radiation exposure by modifying the protocol appropriately.

Introduction

Diagnostic imaging that uses ionizing radiation may sometimes be necessary for a pregnant patient despite the potential risk to the fetus. Typically, when such diagnostic information is needed, it is relating to the health of the mother. When a radiologist or nuclear medicine physician needs to decide if the diagnostic benefits will outweigh the risks of radiation, it is important they have a reasonable estimate of radiation dose to the fetus. In cases where pregnancy is discovered during or after a diagnostic examination, the physician or the patient may request an estimate of the radiation dose received by the fetus. The risks of fetal adverse outcomes, including childhood cancer induction, are small at a dose of 100 mGy and negligible at doses of less than 50 mGy. [1,2] In the case of hybrid imaging where both modalities involve radiation, the fetal dosimetry resulting from both modalities should be considered. One example is positron emission tomography/computed tomography (PET/CT) where the CT scan provides anatomic information, and the PET scan provides information on radionuclide uptake at the tumor site. Fetal dose estimates from CT have been primarily based on Monte Carlo simulations of geometric patient models. [3-5] PET studies of pregnant patients are extremely uncommon, and even ^{18}F-FDG PET studies accidentally performed in pregnant patients are rare. [6-11] Therefore, providing fetal dose estimates from CT and ^{18}F-FDG PET images where the dose can be estimated from the image itself and from dose reports would be helpful to the medical imaging community. In this study, fetal dose estimates for PET/CT scans that are based on a series of pregnant patients in their first, second and third trimester. These images were used to calculate the size-specific dose estimate (SSDE) [12] from the CT scan portion, and the standard uptake value (SUV) and ^{18}F-FDG uptake dose from the PET scan portion using the Medical Internal Radiation Dose (MIRD) formulation. This study will provide the imaging community with dose estimates to the fetus in PET/CT based on patient data, the availability of which is quite rare.

Methods and materials

Pregnant Patient Population

A total of nine ^{18}F-FDG PET/CT scans performed in pregnant patients over an 11 year period at the University of Michigan were analyzed. The axial range of these scans covered the full uterus. The gestational ages of the fetuses of these patients ranged from 3 to 40 weeks. The cohort included two patients in the first trimester of pregnancy, two in the second trimester, and five in the third trimester. Some patients were scanned multiple times during pregnancy and post-partum to ascertain diagnostic information pertaining to the patient. The post-partum scans were included in this study as a way of comparing what dose a fetus might get from a PET/CT scan using standard protocols for non-pregnant patients.

CT Fetal Dose Estimation

The CT portion of the scans were acquired with 120-kVp and 130-kVp acquisition protocols, with the slice thickness varying from 2 to 5 mm. The patients were originally scanned with one of the following scanners: Siemens Biograph Vision 6 PET/CT, Siemens Biograph 40 True Point PET/CT and Siemens Emotion Duo CT/CPS 1062 PET. No oral contrast agent was used for the CT examinations. The PET/CT images of the pregnant mothers' anatomy were at least from the top of the cranium to the upper thigh of the mother. The gestational age was estimated from the clinical data.

CT axial scans of the same nine patients were collected on SIEMENS systems. These images were analyzed retrospectively and the scan parameters were obtained from the DICOM header shown in Table 1. There are two patients that were scanned twice with the fetus at different gestational ages.

Patient#	System	kV, mA, ms	Slice thickness (mm)	Pitch	$CTDI_{vol}$	Weight (kg)	Kernel Recon	DW fetus/overall (cm)	Gestational age (weeks)	Patient perimeter (cm)	Topogram (kV/mA)
1**	Emotion Duo	130, 79, 800	5	1.0	6.74	74.5	B40s	34.9/33.6	17	92.5	130/30
2**	Emotion Duo	130, 47, 800	5	1.0	4.01	66.7	B40s	37.0/35.3	33	102.4	130/30
3	Emotion Duo	130, 47, 800	5	1.0	4.01	53.9	B40s	33.0/32.4	12	81.4	N/A
4	Emotion Duo	130, 47, 800	5	1.0	4.01	72.6	B40s	36.5/32.4	36	99.2	N/A
5δ	Biograph 6	130, 75, 600	5	1.0	4.79	58.6	B30s	35.1/32.4	28	84.3	N/A
6	Biograph 40	120, 60, 500	5	1.0	2.45	54.4	B30s	35.4/33.0	36	87.8	120/29
7†	Biograph 40	120, 40, 500	2	1.0	1.63	69.0	I31f\5	37.4/33.6	14	99.2	120/20
8†	Biograph 40	120, 40, 500	2	1.0	1.63	79.8	I31f\5	38.5/34.8	26	85.6	120/20
9ß	Biograph 40	120, 40, 500	3	1.0	1.46	88.9	I30f\3	39.1/33.5	20	109.0	120/20
10**	Emotion Duo	130, 156, 800	5	1.0	13.35	68.1	B40s	0/35.43	post-partum	92.1	130/30
11ß	Biograph 6	130, 164, 600	4	1.0	12.65	88.53	B31s	0/37.42	post-partum	111.1	N/A
12†	Biograph 40	120, 84, 500	3	1.0	2.98	74.39	I30f\3	0/37.10	post-partum	103.2	120/35
13δ	Biograph 6	130, 162, 600	4	1.0	9.73	62.4	B30s	0/34.97	post-partum	92.09	N/A
14δ	Biograph 6	130, 182, 600	4	1.0	10.49	59.9	B30s	0/34.66	post-partum	86.94	N/A

Table 1. Data collection of human patient routine cases performed for pregnant patients. Patient #8 and patient #9 are the same patient that came in for two separate scans.
***Same patient scanned at 17, 33 weeks and post-partum.*
†Same patient was scanned at 14, 26 weeks and post-partum.
ßSame patient was scanned at 20 weeks and post-partum.
δSame patient was scanned at 28 weeks and twice post-partum.

These CT scans were performed using techniques yielding low doses as shown in Table 1. For all nine cases there was no automatic tube current modulation (ATCM), therefore a constant tube current and kilovoltage was used. For patient numbers 1-5 scanned prior to 2011, the $CTDI_{vol}$ was not reported since this quantity was not an FDA requirement at the time. The CTDIvol was calculated using the output values for a 32 cm phantom of 6.7 mGy/100 mAs in the center and 12.8 mGy/100 mAs at the periphery for the Emotion Duo[13] and Biograph 6[14] scanners. The pitch factor could not be located in the DICOM header for scans from these scanners, so we assumed it to be 1.0.

The CT dose to the fetus was calculated based on the size specific dose estimate (SSDE) method used to calculate organ dose. [15-24] A recent study by Hardy et al.[25] showed a reasonable accuracy (± 25%) with the use of SSDE as a surrogate of fetal dose. The normalized dose coefficient (NDC) scales the

CTDIvol to make it reflect the dose the patient actually receives. The NDC is calculated directly from the patient size surrogates, which include the effective diameter or water-equivalent diameter (Dw). The preferred patient size surrogate is the water equivalent diameter since it directly incorporates attenuation properties from the patient scan. The water-equivalent diameter (D_W) represents the diameter of a cylinder of water that contains the same total x-ray attenuation as that contained within the patient's axial cross section and depends on both the cross-sectional area of the patient and the attenuation of the contained tissues. The method of calculating D_W described in AAPM Report 220[12] was implemented using the following equation

$$D_W = \sqrt{\frac{4}{\pi}\left(\frac{\underline{CT}(x,y)}{1000} + 1\right) \times A_{ROI}} \quad \text{(equation 1)}$$

where D_W is the water-equivalent diameter, $\underline{CT}$ represents the mean CT number within the reconstructed field of view (FOV), and A_{ROI} is the product of the number of pixels in the ROI and the pixel area. Our ROI was inscribed inside the reconstructed DICOM images for each patient. Since the DICOM images are square matrices, we inscribed a circle inside each DICOM image with a diameter equal to the entire width of the image. D_W was calculated from CT axial images as previously described. Corrections were applied to images that were not reconstructed at isocenter.[26] In some cases, when the reconstructed image center was not at isocenter, this ROI could contain "padding" values of -3024 HU. Therefore, we applied a remapping of all of the values inside the circle used to calculate the mean CT number which mapped all signals equal to -3024 to -1000 HU to simulate air. The use of padding values is common to most CT vendors, but the padding value may differ. Failure to correct for this would decrease the DW values. We did not perform any thresholding or connected component analysis of the axial image data prior to calculating D_W. The D_W uses the mean Hounsfield units of the patient habitus taking into consideration the attenuation properties of the patient. The DW was then used to calculate the normalized dose coefficient (NDC) using equation A-1 from the AAPM TG Report 204 replicated in equation 2 here as

$$NDC = a \times exp(-b \times Dw) \quad \text{(equation 2)}$$

where constants a = 3.70469 and b = 0.03671937, the water-equivalent diameter is denoted as D_W, and the normalized dose coefficient is denoted as NDC. The SSDE is simply the product of the NDC and CTDIvol as shown in equation 3,

$$SSDE = NDC \times CTDI_{VOL} \quad \text{(equation 3)}$$

where the $CTDI_{vol}$ for a 32 cm phantom was taken from the patients' dose reports. The average SSDE was taken along the length of the fetus. The absorbed dose to the uterus was used as a surrogate for the absorbed dose to the embryo/fetus as is common practice in medical radiation dosimetry.[23,24] The CT localizer radiographs (or topograms) technique (kVp, mA) is reported in table 1. The dose ranges for the topograms ranges from 0.08-0.13 mGy.

^{18}F FDG Fetal Dose Estimation

The ^{18}F-FDG dose administered for all nine patients in this study was 130 MBq (3.5 mCi). At the time of the injection, it was known to the physician that the patients were pregnant, which is the reason for

such a low injection dose. All pharmacokinetic and dosimetric estimates for ^{18}F-FDG including placental crossover as shown in Table 2.[27]

Patient #	Gestational age (weeks)	SSDE (mGy)	FDG fetus self-dose (mGy)	FDG fetus total dose (mGy)	SSDE + FDG self-dose fetus (mGy)	Fetal self-dose to total fetal dose (%)
1	17	6.9	1.28	1.38	8.2	92.8
2	33	3.8	0.0063	0.0099	3.8	63.6
3	12	4.4	2.18	2.35	6.6	93.6
4	36	3.9	0.0017	0.0034	3.9	50.0
5	28	4.9	0.014	0.021	4.9	67.6
6	36	2.0	0.0017	0.0034	2.0	50.0
7	14	1.2	1.82	1.96	3.0	92.9
8	26	1.2	0.0017	0.025	1.2	68.0
9	20	1.0	0.74	0.80	1.7	92.2
10	post-partum	13.47	4.9 (12) 0.045 (24) 0.0038 (36)	5.2 (12) 0.065 (24) 0.0075 (36)	18.37 (12) 13.52 (24) 13.47 (36)	92.8 (12) 68.5 (24) 51.2 (36)
11	post-partum	11.87	9.2 (12) 0.085 (24) 0.0073 (36)	9.9 (12) 0.12 (24) 0.014 (36)	21.07 (12) 11.96 (24) 11.88 (36)	92.8 (12) 68.5 (24) 51.2 (36)
12	post-partum	2.83	5.0 (12) 0.046 (24) 0.0039 (36)	5.4 (12) 0.067 (24) 0.0077 (36)	7.83 (12) 2.88 (24) 2.84 (36)	92.8 (12) 68.5 (24) 51.2 (36)
13	post-partum	9.99	5.1 (12) 0.047 (24) 0.0040 (36)	5.4 (12) 0.068 (24) 0.0078 (36)	15.09 (12) 10.04 (24) 9.99 (36)	92.8 (12) 68.5 (24) 51.2 (36)
14	post-partum	10.89	5.3 (12) 0.049 (24) 0.0042 (36)	5.7 (12) 0.071 (24) 0.0082 (36)	16.19 (12) 10.94 (24) 10.89 (36)	92.8 (12) 68.5 (24) 51.2 (36)

Table 2. The patient number (year of exam), the gestational age (weeks), the 18F-FDG uptake MIRD calculation using RADAR with interpolation for weeks between 12, 24 and 36 weeks. The injection activity for the post-partum scans were used to calculate the fetus dose at 12, 24 and 36 weeks as indicated in parentheses.

For ^{18}F-FDG dose calculations the fetuses in the first, second and third trimester were rounded to the gestational age at 3, 6, and 9 months. The ^{18}F-FDG fetal self-dose and total dose from both maternal organs and the fetal self-dose were calculated using a table of specific absorption fractions[28] for the following organs: adrenals, brain, breasts, gallbladder wall, LLI wall, small intestine, stomach, ULI wall, heart wall, kidneys, liver, lungs, muscle, ovaries, pancreas, red marrow, bone surfaces, skin, spleen, thymus, thyroid, urinary bladder wall, uterus, fetus and placenta.

The Standard Uptake Volume (SUV) is a simple metric for assessing the amount of activity present in the fetus. The SUV was determined using HERMES software by drawing a contour region of interest (ROI) about the fetus in all slices of the PET image where the fetus is present. The mean, maximum and peak (95% percentile) values were determined over the entire volume of the fetus.

Statistical Analysis

The fetal dose estimates were tested for correlation with each of the following independent measures: gestational age, fetal volume, average water-equivalent diameter of the patient along the length of the fetus, size-specific dose estimate (SSDE), SUV, and percentage of dose from FDG. Stepwise multiple linear regression analysis was performed to assess the partial correlation of each variable.

Results

All data were collected under an IRB-approved protocol in a retrospective manner in which the patient consent was waived. Table 3 shows the following information gathered from the PET scan: mean SUV, standard deviation, the maximum SUV and the 95th percentile SUV, all over the entire volume of the fetus. Table 2 shows the SSDE for 4 cases after 2011, the ^{18}F fetus self-dose, ^{18}F fetus total dose, total dose from SSDE and ^{18}F to fetus and percentage of fetus self-dose to total dose. Figure 1 shows the ^{18}F-FDG fetal self-dose to fetal total dose from organs, including the fetus, of the patient.

Patient #	Gestational age (weeks)	Mean SUV	Standard Deviation	Maximum SUV	95th percentile SUV
1	17	2.30	0.98	7.67	4.20
2	33	4.61	0.98	9.13	6.51
3	12	1.28	0.31	2.64	1.8
4	36	2.71	1.02	9.36	5.18
5	28	2.11	1.01	6.61	4.08
6	36	2.50	1.18	11.71	4.80
7	14	1.24	0.73	7.83	2.66
8	26	1.73	1.45	15.03	4.49
9	20	1.62	0.85	7.28	3.27

Table 3 shows information from the PET images: gestational age, mean SUV over entire fetal volume with standard deviation summed in quadrature, the maximum SUV over the entire fetal volume and 95th percentile SUV over the entire volume.

Figure 1. ^{18}F-FDG fetal self-dose to fetal total dose from organs of patient.

Discussion

To our knowledge, this is the largest series of pregnant patients for whom fetal radiation dose from ^{18}F-FDG and SSDE was calculated. Our data adds considerably to the existing literature about fetal radiation exposure from ^{18}F-FDG PET and CT dose studies of pregnant patients. These patients were not accidentally exposed to ^{18}F-FDG during their pregnancy but rather underwent intentional studies that were performed after adequate consideration of the risks and benefits of ^{18}F-FDG PET in these pregnant patients with malignancy. ^{18}F-FDG is known to cross the placental membrane and accumulate in the fetus[8,23,29-32] and we were able to clearly identify ^{18}F-FDG activity in the fetus inside the gravid uterus, confirming the ability of ^{18}F-FDG to cross the placenta and accumulate in the fetus. There is no scientific literature documenting fetal toxicity associated with ^{18}F-FDG in pregnant women or nonhuman primates. All our patients delivered healthy babies at term.

For visual inspection, figure 2 shows examples of a single CT and corresponding PET image of the fetus for pregnant patients in the first, second and third trimester.

Figure 2. Examples of a single PET, CT and PET/CT fused image for 6 patients in the cohort at gestational age of a) 12 weeks with high concentration of ^{18}F-FDG in the fetal heart b-c) 20 weeks, d-f) 36 weeks to demonstrate 1st trimester, 2nd trimester, and 3rd trimester pregnancy, respectively. The ^{18}F-FDG uptake in the fetus is seen in the PET images.

Our results show that fetal doses from a combined dose from ^{18}F-FDG and SSDE ranges from 1.2 to 8.2 mGy and the SSDE alone ranges from 1.0 to 2.0 mGy, shown in Table 2. These doses are significantly below the threshold of 50-100 mGy considered for deterministic effects to the fetus although fetal dose in this range does not conclusively result in adverse impact to the fetus.[33] Generally, most of the diagnostic studies performed during a mother's pregnancy are below this threshold. However, there is no threshold for stochastic effects, but a discussion about the probability of various deterministic and stochastic effects occurring because of fetal exposure to radiation from CT or ^{18}F-FDG PET in pregnancy is beyond the scope of this article.

It is not uncommon for a pregnant mother to be imaged using CT by itself. According to a large, multicenter study of advanced medical imaging in pregnancy CT, the imaging rates in the United States increased from 2.0 examinations per 1000 pregnancies in 1996 to 11.4 per 1000 pregnancies in 2007, remained stable through 2010, and decreased to 9.3 per 1000 pregnancies by 2016.[32] Fetal dose estimates from CT have been primarily based on Monte Carlo simulations of geometric patient models. One method is the CTExpo software (version 1.5.1; Medizinische Hochschule, Hannover, Germany) [34,35], which estimates organ dose based on simulations performed by Zankl et al at the German National Research Center with the Eva geometric phantom model to represent a standard-size female patient [3,4]. Felmlee et al. demonstrated estimates of CT dose index using Monte Carlo on an anthropomorphic phantom.[5] Using Monte Carlo, Ratnapalan et al.[36] and Lazarus et al.[37] reported that normalized fetal CT dose ranges from 7.3-14.3 mGy/100 mAs and mean dose of 17.1 mGy (range of 8–44 mGy), respectively. Goldberg-Stein et al. looked at a series of 54 patients and estimated mean fetal dose to be 24.8 mGy (range of 6.7–56 mGy).[38] Doses to the fetus from a single-acquisition abdominal-pelvic CT examination have ranged between 10-50 mGy in phantom and clinical studies. Hurwitz et al.[39] estimated fetal dose by using physical measurements from internal dosimeters in an anthropomorphic phantom that was modified to represent a newly pregnant patient and a patient who was 3 months pregnant from 1.52 to 3.22 cGy. Since the patients in our study were known to be pregnant prior to the scan, the technique on the scanner may have been set to give the lowest possible $CTDI_{vol}$ which was indicative of the AEC being turned off. While $CTDI_{vol}$ is often provided, the uniform cylindrical phantom does not represent the gross anatomy of a pregnant patient. The SSDE is a quantity that describes the absorbed dose to the patient that scales the $CTDI_{vol}$ with a scaling factor based on the patient's size and attenuation.[12,40] This metric will be required to be reported by vendors soon, though it will likely be an average SSDE over the entire patient range. Hardy et al.[25] calculated the CTDIvol-to-fetal-dose coefficients for tube current modulated and fixed tube current CT examinations of pregnant patients of various gestational ages and reported the SSDE. Moore and Brady et al.[24] provided a method for estimating SSDE to an organ where the conversion factor for the uterus was utilized in this study. Existing methods for the estimation of fetal dose for pregnant patients undergoing CT examinations assume early term pregnancy in a single-size patient model with an average, non-varying maternal anatomy. These dose estimates do not consider natural variations, such as fetal

presentation and gestational age. Differences in these attributes can cause overestimation or underestimation of up to 100%.[41] Angel et al.[42] used Monte Carlo simulations to estimate fetal dose in CT for a range of gestational age and patient sizes and found no significant correlation between gestational age and fetal dose. The fetal age, and maternal body habitus, fetal estimated doses using patient data between 1.1 and 21.9 mGy have been reported for CT.

^{18}F-FDG PET studies of pregnant patients are extremely uncommon, and even ^{18}F-FDG PET studies accidentally performed in pregnant patients are rare.[6-11] Because adequate and accurate data regarding ^{18}F-FDG uptake by the fetus are not available other than the very few case reports of accidental exposure, it is difficult to get an estimate of fetal radiation exposure from ^{18}F-FDG PET in pregnant patients. As a result, most estimates of fetal dose from ^{18}F-FDG PET are based on models of exposure to the fetus from radiation from the mother, and do not consider self-dose from the fetus itself. Those studies that have been published are mostly based on data from either nonhuman primates and mathematic models.[8-11] Recent case reports by Zanotti-Fregonara et al.[29,43] have raised the possibility that ^{18}F-FDG dose to the fetus in early pregnancy may be higher than estimated by current dosimetric standards. Hence, there is a need to have more data to establish the accurate fetal dose exposure. There have been a few studies that have looked at fetal dose from mothers having a PET scan using ^{18}F-FDG [44-47]. The Society of Nuclear Medicine and Molecular Imaging (SNMMI) has provided a Nuclear Medicine Radiation Dose Tool for ^{18}F-FDG exams for different patient models including pregnant women in early stage of pregnancy, 3, 6 and 9 months into their pregnancy. This model provides two dosimetry tables [48,49] to perform these calculations and user inputs the initial activity. The first is the ICRP 128 (2015) that bases their dosimetry model on anthropomorphic phantoms and effective doses are based on organ weighting factors from ICRP 60. Their tables contain a mix of published estimates from ICRP (Publications 53, 80, 106) and dosimetry provided by Stabin et al.[27] The second is RAdiation Dose Assessment Resource (RADAR 2017) generated dose estimates using a set of anthropomorphic phantoms[27], which are based on the recommended body and organ masses given in ICRP Publication 89 (ICRP 2003). This study uses PET scans of pregnant patients to calculate the SUV, fetal self-dose and total fetal dose from the organs of the patient from and based on our findings we determined that ^{18}F-FDG dose is exceedingly low. The fetal heart contains the highest concentration of uptake of ^{18}F-FDG as shown in Figures 3-7. Figure 3-7 show examples of ^{18}F-FDG in the fetal heart for patients in their 2nd and 3rd trimester, respectively. Supplemental Figure 1 shows a patient that is well into their third trimester with ^{18}F-FDG in the fetal heart, like that shown in Figure 7. Figure 2a shows a higher concentration of ^{18}F-FDG uptake in the fetal heart.

Figure 3 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients in their 2nd trimester at 20 weeks.

Figure 4 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients in their 2nd trimester at 26 weeks.

Figure 5 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients in their 2nd trimester at 28 weeks.

Figure 6 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients well into their 3rd trimester at 33 weeks.

Figure 7 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients well into their 3rd trimester at 36 weeks.

For PET/CT, the total fetal estimate radiation dose is the sum of CT exposure, maternal gamma irradiation, fetal beta and fetal gamma irradiation. One method for calculating t fetal dose estimates for CT is the ImPACT CTDosimetry dose calculator (CTDosimetry.xls, version 0.99; ImPACT, London, England) [50], which is based on Monte Carlo simulations performed by the National Radiological Protection Board [51] with the use of a geometric Medical Internal Radiation Dose (MIRD) phantom model [52].

A limitation to our study is that, despite our sample of pregnant patients being the largest ever reported, it is still relatively small. Another limitation is that we considered the fetus to be an oval shape in PET images for calculating SUV. It was difficult to contour the perimeter of the fetus especially for first trimester, however this oval was confined as much as possible to the fetus for each PET slice. We also rounded the gestational age upwards to 3, 6 and 9 months for the MIRD calculations. Lastly, we did not attempt to estimate the dose uncertainties for this study.

Conclusion

This is the first study where fetal doses have been determined from CT and PET images of pregnant patients. These types of images from pregnant patients are rare. Fetal self-dose from ^{18}F for the 1st, 2nd and 3rd trimester range from 2.18 mGy, 0.74-1.82 mGy and 0.017-0.0017 mGy, respectively. The range of SSDE for the CT scan and fetal self-dose for the PET scan ranges from 1.2-8.2 mGy. Our data indicate that the fetal radiation exposure from ^{18}F-FDG PET and CT performed, when medically necessary, in pregnant women with cancer is low. All efforts should be made to minimize the fetal radiation exposure while maintaining diagnostic accuracy by modifying the protocol appropriately.

Disclosure

No potential conflicts of interest relevant to this article exist.

Key Points

Question: Is there a risk to the fetus for pregnant patients undergoing a positron emission tomography (PET) and computed tomography (CT) scan?

Pertinent findings: In a study involving 9 pregnant patients who underwent PET/CT, our data suggests that the fetal radiation exposure from ^{18}F-FDG PET and CT performed, when medically necessary, in pregnant women with cancer is low. The fetal self-dose from ^{18}F-FDG for the 1st, 2nd and 3rd trimester range from 2.18 mGy, 0.74-1.82 mGy and 0.017-0.0017 mGy, respectively, and the range of SSDE and fetal self-dose ranges from 1.2-8.2 mGy.

Implications for patient care: While it is not encouraged for pregnant patients to undergo PET/CT scans, the data suggests that if a scan was needed to assess the health of the patient, the dose to the fetus would not put the fetus at risk. All efforts should be made to minimize the fetal radiation exposure by modifying the protocol appropriately.

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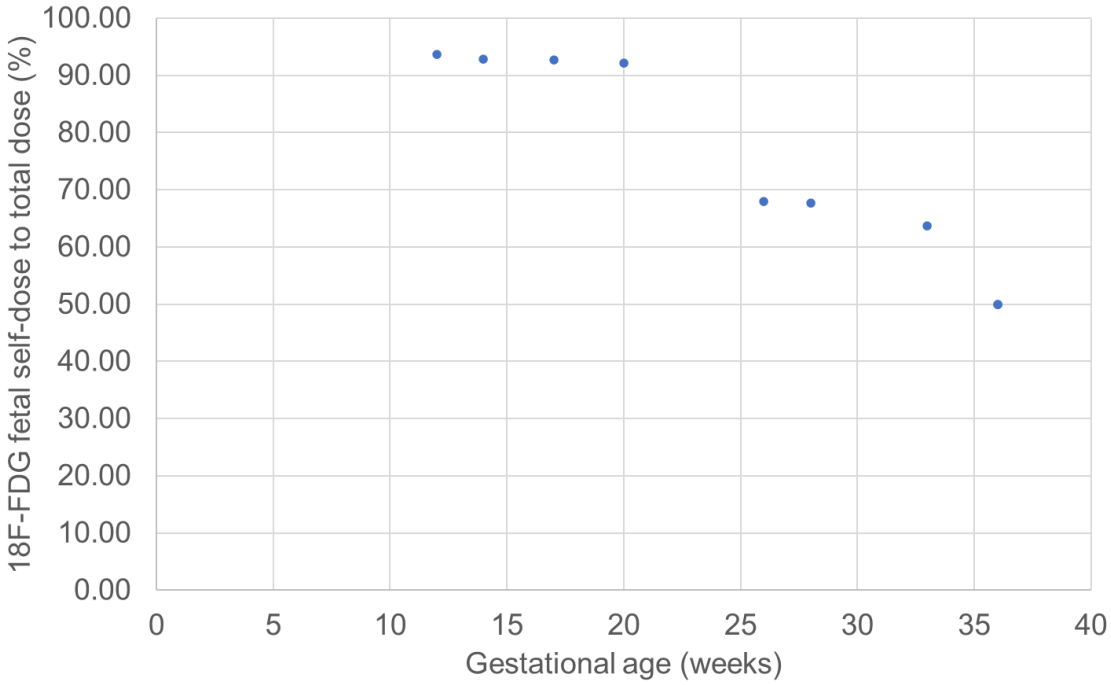


Figure 1. ^{18}F-FDG fetal self-dose to fetal total dose from organs of patient.

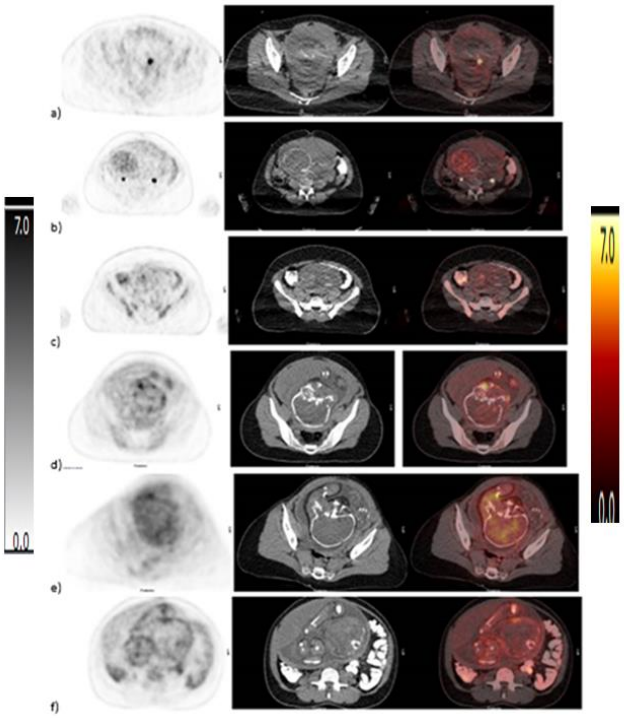


Figure 2. Examples of a single PET, CT and PET/CT fused image for 6 patients in the cohort at gestational age of a) 12 weeks with high concentration of ^{18}F-FDG in the fetal heart b-c) 20 weeks, d-f) 36 weeks to demonstrate 1st trimester, 2nd trimester, and 3rd trimester pregnancy, respectively. The ^{18}F-FDG uptake in the fetus is seen in the PET images.

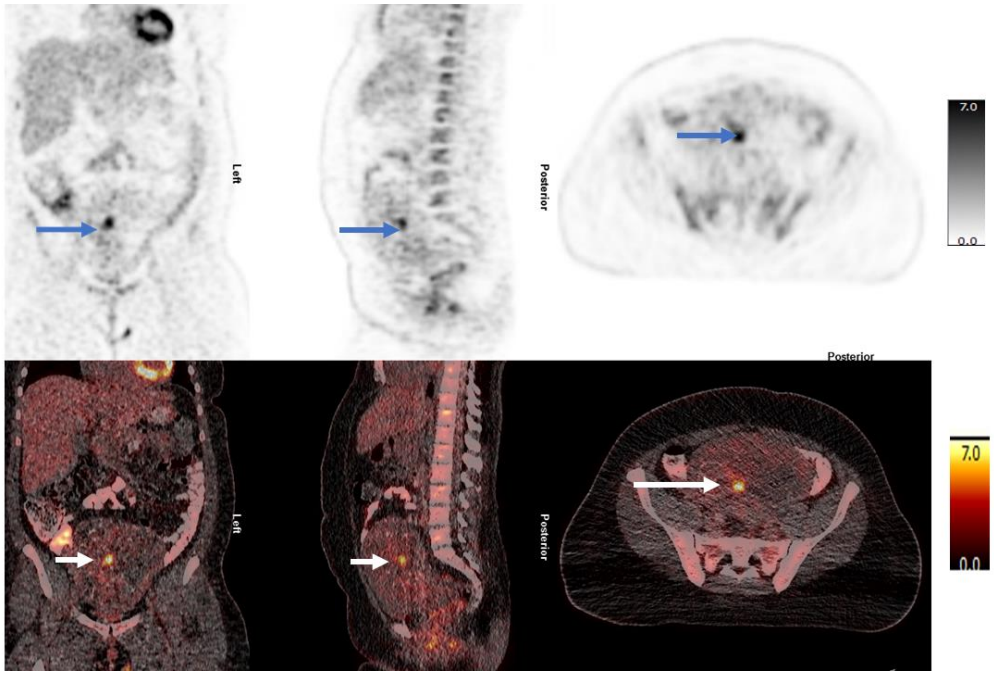


Figure 3 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patient in the second trimester at 20 weeks.

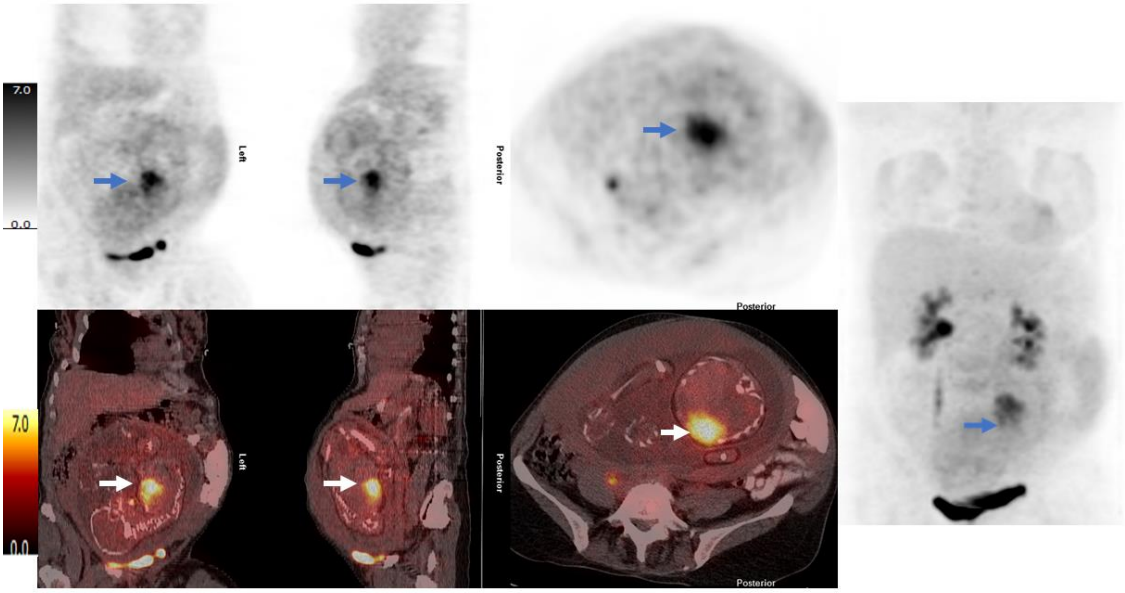


Figure 4 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patient in the second trimester at 26 weeks.

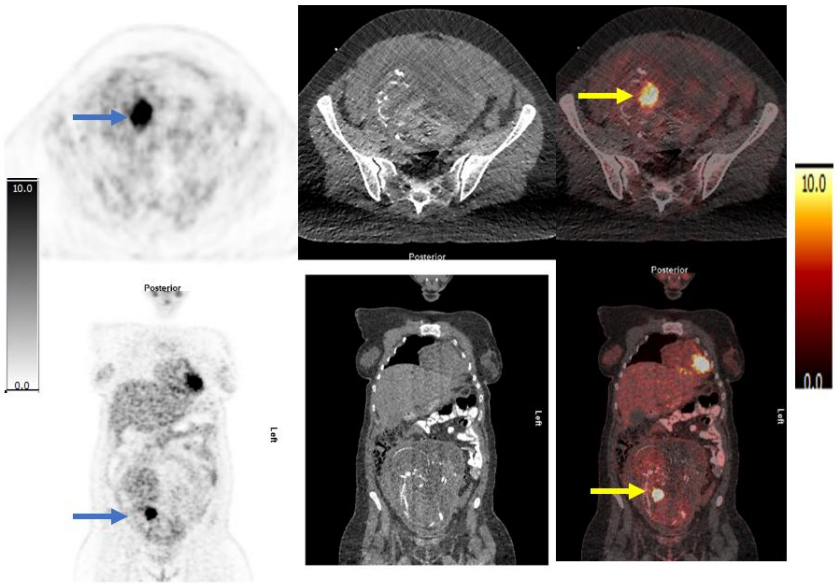


Figure 5 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patient in the second trimester at 28 weeks (entering third trimester).

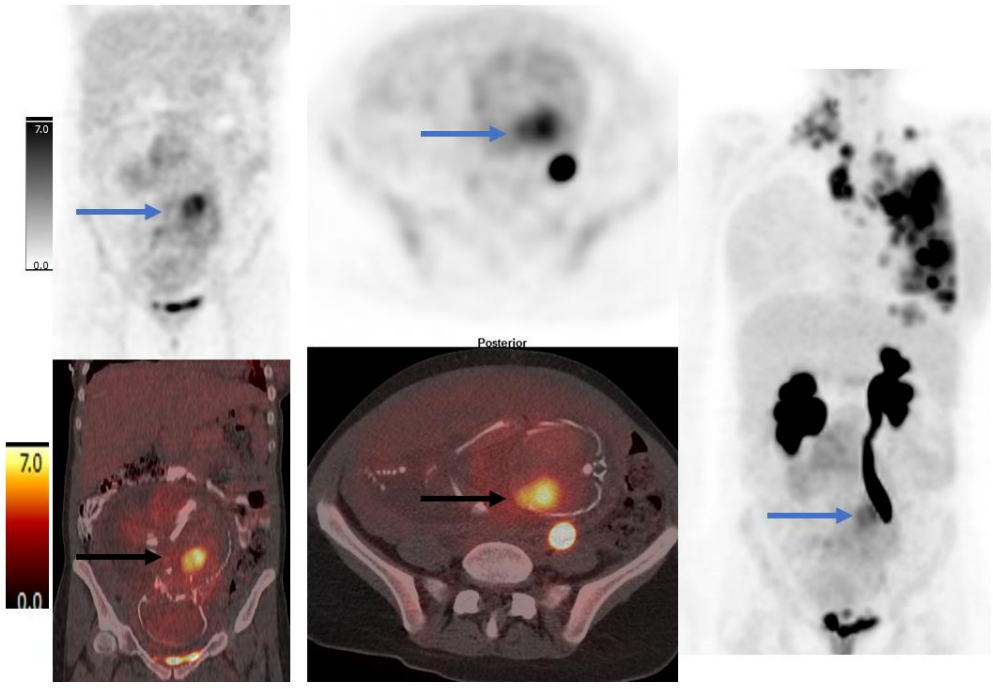


Figure 6 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients well into the third trimester at 33 weeks.

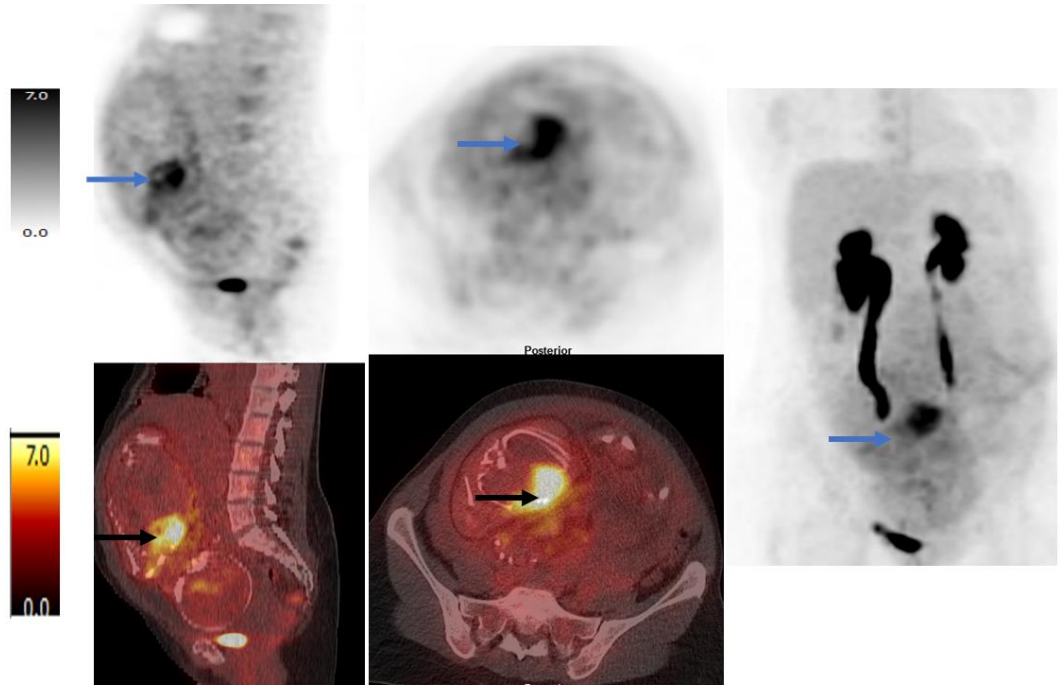
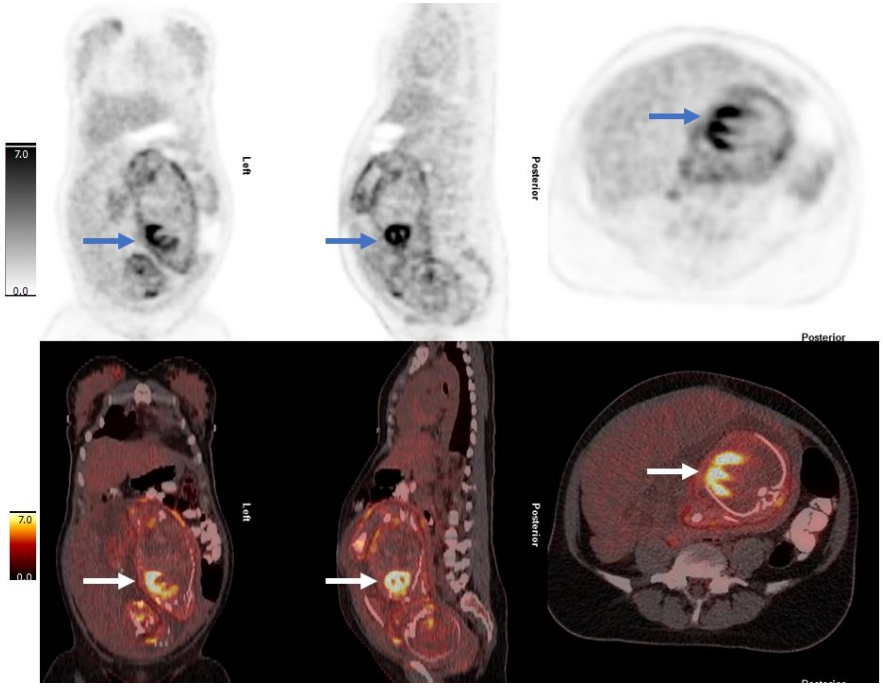
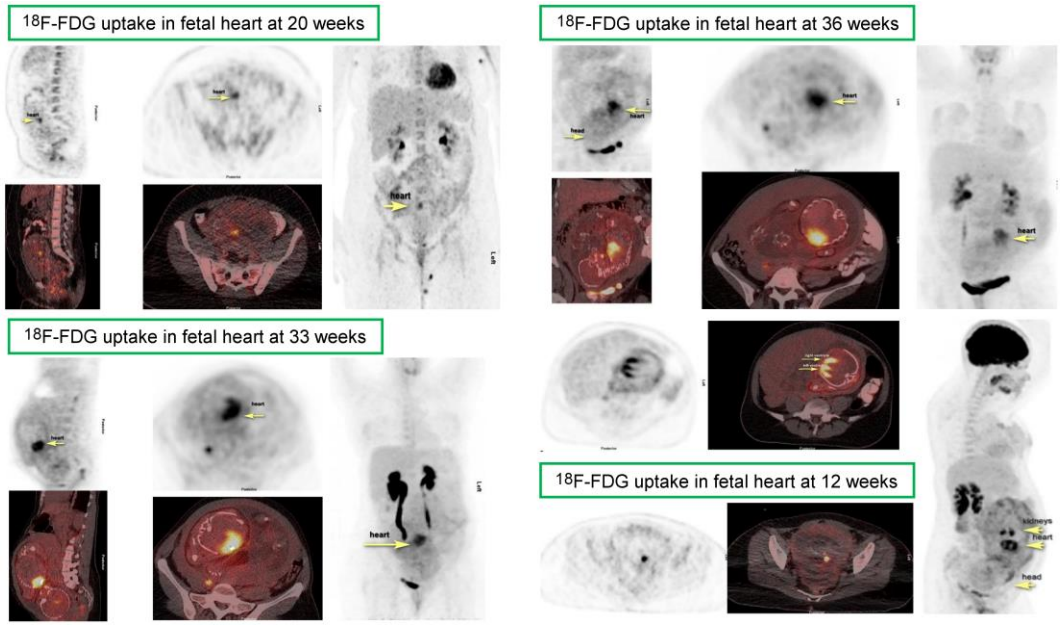


Figure 7 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients well into the third trimester at 36 weeks.



Supplemental figure 1 shows example of concentrated uptake of ^{18}F-FDG in the fetal heart for patients well into the third trimester at 36 weeks.



Graphical Abstract