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Gamma Dose to a Fetus from Internal and External Sources

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GAMMA DOSE TO A FETUS FROM INTERNAL AND EXTERNAL SOURCES

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ABSTRACT

The purpose of this study was to use the QAD computer code to calculate the dose received by a fetus from external and internal sources to which the mother is exposed. The changes in Chapter 10, part 20 of the Code of Federal Regulations that will be put into effect January 1, 1994, will require that radiation doses be reported not only for the whole body but to specific organs and the fetus as well. Fortunately, the computer program QAD can provide health physicists and other persons responsible for monitoring radiation exposure of individuals with an accurate, easy to use method for calculating dose rates. Dr. Nicholas Tsoulfanidis and Katherine Phillips developed a model of the human body with the combinatorial geometry capabilities of the code that was used to compute radiation exposure to organs such as the lungs, liver, eyes, and kidneys from external radiation sources [3]. The goal of the present investigation was to extend that application into modeling the body of pregnant woman. The body model developed in reference 3 was modified following the changes during pregnancy and dose rates were calculated at many locations in the position of the fetus and at the position of a pocket dosimeter. Point sources of ^{60}Co, ^{137}Cs, and ^{131}I, were assumed to be the radiation sources.

INTRODUCTION

The proposed changes of the Code of Federal Regulations Chapter 10, part 20 (10 CFR 20) present problems to health physicists concerned with calculating and reporting doses received by individuals. Whereas exposures to radiation workers are currently reported as whole body doses with some special attention given to the extremities and eyes, the changes will require employers to report dose rates to specific internal organs. In addition, dose limits received in a radiation area will not only apply to the mother during a pregnancy, but specific limits will be established for the embryo/fetus as well. This study presents a method that can be used for the calculation of the dose received by a fetus when the mother is exposed to an external source of radiation.

In 1991, Dr. Nicholas Tsoulfanidis and Katherine Phillips published a paper which was based on the QAD computer code. A model of the human body, a "phantom", was developed and used to obtain organ to surface dose ratios from various external radiation sources [3]. The specific case of a pregnant woman and fetus was not addressed, and thus this paper is a continuation of reference 3. QAD is a point kernel code utilizing gamma ray buildup factors which are based on the geometric progression form established by the American National Standards (ANS)-6.4.3 Standards Committee. QAD provides results in the form of the dose received by a "detector." The detector is simply a point at a location specified by the user. The most significant advantage in using QAD for these studies is its combinatorial geometry capabilities. In this code, complicated geometries such as the human body can be represented accurately. Also, input of the geometric progression buildup factors is less cumbersome for the user and can be run much more quickly than a Monte Carlo code. A limitation of QAD is the requirement to use a buildup factor for only one material to represent the shielding thickness, regardless of the number of materials a gamma ray crosses to reach the point of interest. Since the human body is ninety percent water and different tissues and organs have similar composition, this limitation of QAD coding introduced only minor error.

The first part of this paper outlines the methodology and final dimensions used in modifying the body model. Next, dose rates received from each source are tabulated. Finally, the results are analyzed and specific recommendations are given for individual health physicists and the profession as a whole.

METHODOLOGY

Development of the Body Model

The body model of reference 3 provided a basis for developing the new model. The original phantom was designed with dimensions and masses of organs taken from reports of the International Commission of Radiological Protection (ICRP) and the Medical Internal Radiation Dose Committee (MIRD). Figure 1 shows the original body model and Table I gives the dimensions used for that model.

Information about the dimensions of a pregnant woman's body was obtained from Dr. Matthews, a Rolla radiation oncologist, Dr. Judy Miles, geneticist, and from several texts. First, the mass and size of the fetus was determined by month. For simplicity, values were taken in the middle of each month. The fetus was not represented in detail because this study was not intended to analyze doses to specific organs of the embryo. Therefore, a cylinder for which the dimensions changed from month to month was chosen to represent the fetus. From the total mass and the length of the cylinder, its radius was calculated assuming the fetal tissue density to be that of water, 1 gram per cubic centimeter. Table II gives these dimensions by month.

Next, the enlargement of the abdomen due to growth of the fetus and mass increases of various organs and tissues was considered. The abdomen enlargement was represented as a hemisphere centered at the body center line. When determining the mass and volume increases of the abdomen, only weight increases of the fetus, the placenta, the amniotic fluid, and the uterus were included (Table III). From this data it was possible to calculate the radius of the

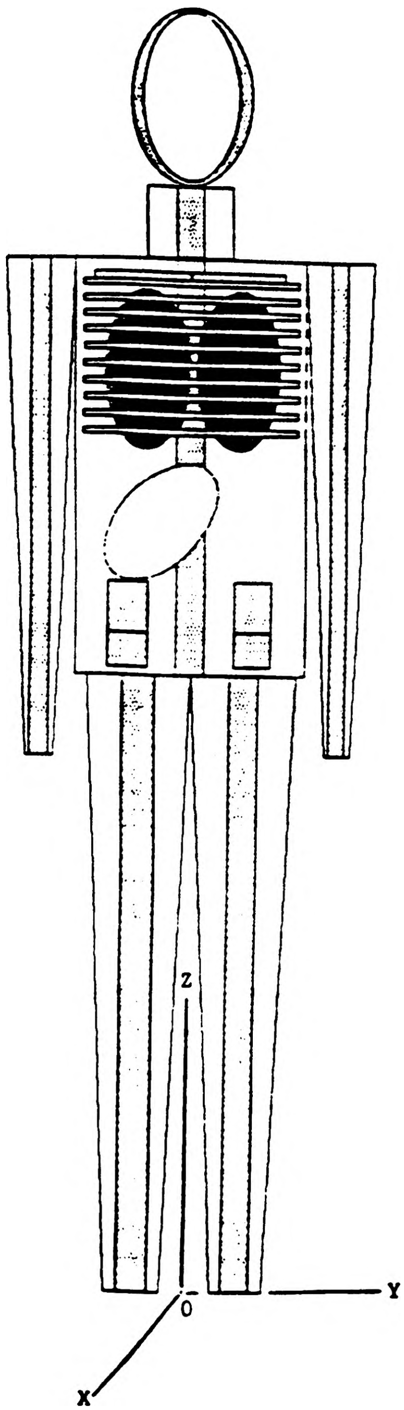

Figure 1: Model of the human phantom.

Organ or part of human body	Geometric body[a]	Dimensions (cm)[b]
Leg (2)	TRC	L = 86.00, R1 = 4.00, R2 = 7.50
Leg bone (2)	RCC	L = 86.00, R = 2.28
Torso	REC	L = 58.00, R1 = 13.5, R2 = 16.5
Arm (2)	TRC	L = 69.00, R1 = 2.00, R2 = 5.00
Arm bone (2)	RCC	L = 69.00, R = 1.48
Neck	RCC	L = 10.00, R = 6.00
Skull	ELL	L = 25.00, Rmn = 8.50, Rmx = 12.5
Head (int.)	ELL	L = 23.45, Rmn = 7.72, Rmx = 11.72
Lung (2)	ELL	L = 22.00, Rmn = 6.05, Rmx = 11.0
Liver	ELL	L = 20.00, Rmn = 6.60, Rmx = 10.0
Clavicle (2)	RCC	L = 13.40, R = 0.80
Ribs (10) (outer)	REC	L = 1.00, Rmn = 12.5, Rmx = 15.5
Ribs (10) (bone)	REC	L = 1.00, Rmn = 11.7, Rmx = 14.7
Scapula (2)	REC	L = 16.00, Rmn = 0.30, Rmx = 4.0
Spinal cord	RCC	L = 58.00, R = 0.50
Spine (bone)	RCC	L = 58.00, R = 2.07
Spinal cord (neck)	RCC	L = 10.00, R = 0.50
Spine (bone neck)	RCC	L = 10.00, R = 2.07
Pelvic bone (2)	REC	L = 15.00, Rmn = 1.00, Rmx = 5.0
Pelvic bone (2)	REC	L = 5.00, Rmn = 0.64, Rmx = 5.0
Breast (2)	SPH	R = 7.62

[a] RCC, right circular cylinder; REC, right elliptical cylinder; ELL, ellipsoid; TRC, truncated right angle cone; SPH, sphere.

[b] L, height or length of cylinder or cone.

Table I: Geometric bodies used for the human phantom.

Table II: Fetus and representative cylinder dimensions for the months of gestation.

Month of Gestation	Week of Gestation*	Fetus Mass(g)	Cylinder Length(cm)	Cylinder Radius(cm)
3	(10,11)	4.0	6.0	0.44
4	(14,15)	70.0	12.5	1.34
5	(19,20)	240.0	20.5	1.93
6	(23,24)	501.0	27.5	2.41
7	(28,29)	1001.0	35.0	3.02
8	(32,33)	1675.0	40.0	3.65
9	(36,37)	2340.0	45.0	4.07

* The values were taken between the two given weeks in the middle of the corresponding month.

Table III: Dimensions and mass of maternal body during gestation.

Month of Gestation	Week of Gestation	Placenta Wt(g)	Amniotic Fluid(g)	Uterus Wt(g)	Volume (cm^3)*	Radius (cm)*
3	(10,11)	20.0	30.0	140.0	194.0	4.52
4	(14,15)	80.0	160.0	210.0	520.0	6.28
5	(19,20)	170.0	350.0	320.0	1080.0	8.01
6	(23,24)	280.0	530.0	380.0	1691.0	9.31
7	(28,29)	376.0	710.0	510.0	2597.0	10.74
8	(32,22)	470.0	770.0	660.0	3575.0	11.95
9	(36,37)	560.0	790.0	810.0	4500.0	12.90

* Volume and radius of the hemisphere representing the abdominal gain.

hemisphere. Other mass increases in the breasts, blood, extracellular extravascular fluid, and maternal reserves, do not contribute significantly to shielding of the fetus and thus were neglected.

Finally, the position of the cylinder representing the fetus was determined. The cylinder itself had the same composition as that of the phantom because the densities of fetal and maternal tissue are virtually the same and therefore the effective shielding does not change. The positions where the dose was recorded were considered to be locations inside the cylinder and thus represented the dose that would have been received by the fetus. A total of seven body models were formed with different abdominal and fetal dimensions (Tables II and III). The seven body models corresponded to months three through nine of gestation.

Placement of Sources and Detectors

The sources of radiation were point isotropic sources in the form of radioactive particles. Of considerable concern to workers in a radiation area is the existence of "hot particles" of contamination that can become attached to clothing or the skin. Hot particles can be accurately represented as point isotropic sources. To represent a hot particle attached to clothing, ^{60}Co was assumed placed at the left shoulder [Position B in figure 2). To represent contamination on the hands, ^{137}Cs was assumed placed on the left hand [Position C in figure 2]. Both ^{137}Cs and ^{60}Co were assumed placed at a position outside the body [Position A in figure 2] to represent an external source. Last, ^{131}I was assumed positioned at the thyroid gland (Position D in figure 2) to analyze the dose the fetus would receive if the mother were to be injected with radioiodine. Seven detectors at positions where the dose was to be calculated were placed in the cylinder representing the fetus and one was placed at the upper front left of the chest at the approximate position of a pocket dosimeter. The doses in units of rem/hour from the sources mentioned above are given in Tables IV through VIII.

DISCUSSION OF RESULTS

In general, the average dose increased during gestation though the maternal shielding also increased. This suggests that during the early weeks of pregnancy, when the embryo is most sensitive to radiation, it is well protected by the pelvic bones. Dose trends to specific detectors depended on the location of the source. For instance, for ^{137}Cs located on the left fingertip, the dose rates calculated at the detectors furthest left were substantially higher than the dose rates calculated at the furthest right detectors. Similarly, for ^{131}I the detector closest to the source at the top of the cylinder representing the fetus received the largest dose. The difference in dose rates was most marked for the ninth month when the length of the cylinder and the distance between detectors is greatest. Last, it is interesting to note that though sources A and B were assumed located at comparable distances from the fetus and outside the body, the dose rates from B (at the shoulder) were much less than from source A (20 centimeters away from the body). The difference can be attributed to the fact that gamma rays from source A traveled most of the

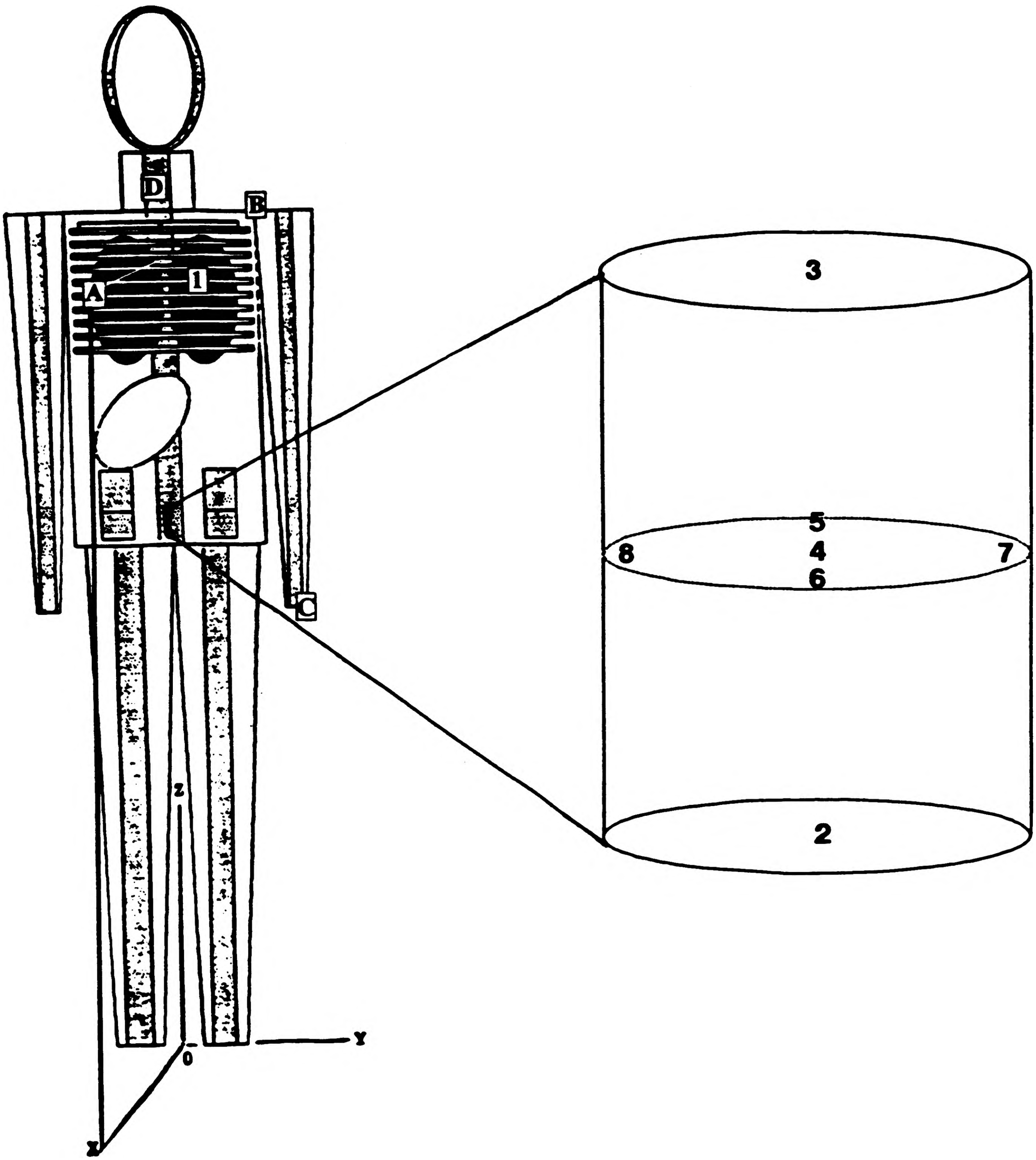

Figure 2: Assumed positions of sources and detectors.

distance to the fetus through air which does not attenuate gamma rays as well as body tissue. Gamma rays from source B, on the other hand, traveled the entire distance through the body.

Clearly, these results are useful for determining appropriate courses of action to take to protect the fetus. Furthermore, the models representing the mother's body during pregnancy can be used to calculate the dose rate to the fetus for any other source location or geometry.

RECOMMENDATIONS

The results clearly show that a significant radiation dose is received by the fetus when the mother is exposed to radiation even in the early months of gestation. Therefore, women working in radiation areas should be strongly encouraged to report a pregnancy to their employer as soon as they are aware of it so that proper precautions can be taken. These precautions could include shielding of the abdominal area when practical and a reduction in the amount of time the mother spends in radiation areas. Also, it is of particular interest to note the substantial dose received by the fetus by ^{131}I at the thyroid gland. This fact should encourage doctors administering radiation treatment to any woman of child bearing age to consider the possibility of pregnancy before commencing treatment.

Last, it may be useful for health physicists to modify the body model to represent different body types (overweight, underweight, etc.). With this model as a basis, health physicists could manage these calculations easily with QAD.

Table IV: Dose rates (rem/hour) from a ^{60}Co at the shoulder (position B).

	Detector*						
Month	2	3	4	5	6	7	8
3	1.46E-1	3.02E-1	2.07E-1	2.07E-1	2.06E-1	2.09E-1	2.04E-1
4	1.46E-1	5.45E-1	2.86E-1	2.88E-1	2.84E-1	3.00E-1	2.70E-1
5	1.46E-1	1.25E1	4.35E-1	4.37E-1	4.29E-1	4.75E-1	3.89E-1
6	1.46E-1	2.65E1	6.22E-1	6.24E-1	6.08E-1	7.15E-1	5.35E-1
7	1.46E-1	5.66E1	9.08E-1	9.10E-1	8.77E-1	1.01E1	7.56E-1
8	1.46E-1	1.15E1	1.55E1	1.55E1	1.46E1	1.98E1	1.19E1
9	1.46E-1	1.15E1	1.55E1	1.54E1	1.45E1	2.04E1	1.16E1

* Detector 1 was located at chest level. The dose was 1.37E1 rem/hour

Table V: Dose rates (rem/hour) from a ^{137}Cs at the fingertip (position C).

	Detector*						
Month	2	3	4	5	6	7	8
3	1.76E1	9.80E-1	1.94E1	1.34E1	1.34E1	1.39E1	1.29E1
4	1.76E1	5.46E-1	1.02E1	1.03E1	1.02E1	1.17E1	8.98E-1
5	1.76E1	2.35E-1	7.11E-1	7.13E-1	7.07E-1	8.54E-1	5.91E-1
6	1.76E1	1.01E-1	5.13E-1	5.13E-1	5.10E-1	6.01E-1	4.09E-1
7	1.76E1	4.81E-2	3.41E-1	3.41E-1	3.34E-1	3.87E-1	2.74E-1
8	1.76E1	1.74E-2	1.84E-1	1.83E-1	1.79E-1	2.33E-1	1.56E-1
9	1.76E1	1.74E-2	1.84E-1	1.83E-1	1.78E-1	2.42E-1	1.53E-1

* Detector 1 was located at chest level. The dose was 1.76E1 rem/hour

Table VI: Dose rates (rem/hour) from a ^{60}Co at postion A outside the body.

	Detector*						
Month	2	3	4	5	6	7	8
3	1.80E1	2.35E1	2.05E1	1.97E1	2.13E1	2.05E1	2.05E1
4	1.72E1	2.86E1	2.31E1	2.04E1	2.60E1	2.30E1	2.30E1
5	1.57E1	3.60E1	2.66E1	2.22E1	3.18E1	2.66E1	2.66E1
6	1.46E1	3.88E1	2.97E1	2.36E1	3.74E1	2.97E1	2.97E1
7	1.34E1	3.14E1	3.28E1	2.44E1	4.41E1	3.27E1	3.27E1
8	1.25E1	2.94E1	3.62E1	2.53E1	5.22E1	3.58E1	3.58E1
9	1.18E1	2.94E1	3.62E1	2.45E1	5.45E1	3.58E1	3.58E1

* Detector 1 was located at chest level. The dose was 7.09E1 rem/hour

Table VII: Dose rates (rem/hour) from a ^{137}Cs at postion A outside the body.

	Detector*						
Month	2	3	4	5	6	7	8
3	1.10E1	1.46E1	1.27E1	1.21E1	1.33E1	1.27E1	1.27E1
4	1.05E1	1.80E1	1.44E1	1.25E1	1.64E1	1.44E1	1.44E1
5	9.31E-1	2.29E1	1.67E1	1.37E1	2.03E1	1.67E1	1.67E1
6	8.50E-1	2.48E1	1.87E1	1.45E1	2.40E1	1.87E1	1.84E1
7	7.67E1	2.39E1	2.08E1	1.50E1	2.84E1	2.07E1	2.04E1
8	7.02E-1	1.86E1	2.30E1	1.56E1	3.38E1	2.27E1	2.27E1
9	6.55E-1	1.86E1	2.30E1	1.51E1	3.82E1	2.27E1	2.27E1

* Detector 1 was located at chest level. The dose was 4.59E1 rem/hour

Table VIII: Dose rates (rem/hour) from a ^{131}I at the thyroid gland (postion D).

	Detector*						
Month	2	3	4	5	6	7	8
3	5.46E-5	4.02E-4	1.42E-4	1.41-4	1.42E-4	1.42E-4	1.42E-4
4	5.46E-5	2.14E-3	3.47E-4	3.4E-4	3.49E-4	3.45E-4	3.45E-4
5	5.46E-5	2.22E-2	1.12E-3	1.1E-3	1.13E-3	1.22E-3	1.22E-3
6	5.46E-5	1.72E-1	3.13E-3	2.9E-3	3.13E-3	3.50E-3	3.50E-3
7	5.46E-5	1.86E-2	9.23E-3	8.6E-3	9.19E-3	1.05E-2	1.05E-2
8	5.46E-5	3.50E1	3.98E-2	3.5E-2	3.91E-2	4.56E-2	4.56E-2
9	5.46E-5	3.56E1	3.98E-2	3.5E-2	3.87E-2	4.54E-2	4.54E-2

* Detector 1 was located at chest level. The dose was 2.48E1 rem/hour

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