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PEDIATRIC PHANTOMS FOR USE IN DOSIMETRIC CALCULATIONS*

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Estimating absorbed doses to children from external and internal radiation sources has become important to the nuclear industry and pediatric nuclear medicine. The Medical Physics and Internal Dosimetry Section at ORNL has recently completed the design of mathematical representations of children of ages newborn, 1-year, and 5-years old. These mathematical representations will be referred to as pediatric phantoms. Using these phantoms, relevant energy deposition data have been developed which establish a meaningful model for use in estimating radiation dose to children.

For several years, members of this Section have developed the computer techniques to estimate fractions of x-ray or gamma-ray energies absorbed in the 22 tissue organs, 10 skeletal parts, and lungs of an adult phantom. This phantom is described in MIRD Pamphlet No. 5, and is shown, in part, in Slide 1. Absorbed fractions are calculated in this geometry with an IBM-360, Model 91 computer using Monte Carlo techniques to transport photons.

Until these pediatric phantoms were developed, simple geometrical shapes or similitude phantoms were used to represent a child when dose estimates were

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calculated. Similitude phantoms, phantoms of ages younger than the adult, were obtained by shrinking each of the three regions of the adult phantom--head, trunk, and legs--by constant factors chosen to be representative of the particular age. All organs within each region were "shrunk" isotropically and changes in organ shape and location were ignored. Also, all the organs in the trunk, for instance, would have the same relative location in each phantom. Five similitude phantoms were developed as shown in Slide 2. These phantoms have been used extensively in the evaluation of the exposure of children even though it was recognized that these similitudes phantoms represented children only to a first approximation.

However, the child is not merely an adult shrunk by a constant factor; the physiological geometry of a child is different from that of an adult. For example, (1) the weight of the head with respect to total body weight is greater for a child than an adult, this is taken into consideration for the similitude phantoms, (2) some internal organs, such as the thymus gland, are larger with respect to other major organs in the child, (3) the bone marrow of a newborn and a 1-year old is primarily red where in an adult the bone marrow is approximately 50% red and 50% yellow, and (4) the trunk of a child is more nearly circular than the adult trunk (which is best represented by an ellipse). Such factors as these preclude the possibility of making meaningful dose estimates to radiosensitive organs such as the gonads and red bone marrow.

Experts agree that until pediatric phantoms are designed and absorbed dose calculations performed, there would always be doubt as to the accuracy of using the similitude phantoms. The Medical Internal Radiation Dose

Committee (MIRD) of the Society of Nuclear Medicine has formed a task group to work on pediatric phantoms. Dr. Adelstein of the Department of Radiology, Harvard Medical and Childrens Hospital and the chairman of this group has encouraged our work on these phantoms.

Mathematical representations of the newborn, 1-year old and 5-year old children were developed using data from anatomical references and the ICRP Task Group on Reference Man as a basis for gross phantom geometries and organ sizes, shapes and weights. These pediatric phantoms each consist of head, trunk, and leg regions with a skeletal system and 22 internal organs. The mathematical descriptions of these phantoms have been coded into Fortran computer language for use with a cross-section plotting routine or with a photon transport code.

Horizontal chest cross sections of the 1-year old, 5-year old and adult phantoms are shown in Slide 3. Note in particular quasi-circular shape of the 1-year old compared to the elliptical shape of the adult. It is best to compare the ribs since arms are included as part of the trunk region.

A Monte Carlo photon transport code is used to calculate absorbed fractions of energy deposited in different target organs from a radionuclide distributed in a source organ. Photon absorbed fraction calculations for technetium-99m have been performed for the pediatric phantoms and the corresponding similitude phantoms. Comparisons have been made for a variety of target organs where the liver, red bone marrow and bladder contents were designated as source organs. The NEXT SLIDE (Slide 4) shows percentage differences between the pediatric and similitude phantoms where the pediatric phantoms are used as the standards. The negative signs are used to indicate when the calculated doses were lower for the pediatric phantoms than the similitude ones. As can be seen, absorbed doses for radiosensitive organs such as the gonads and red bone marrow varied from -150% to 88%.

I would like to show next how these new pediatric phantoms are useful to pediatric nuclear medicine. We have studied, for example, the radiopharmaceutical technetium-99m sulfur colloid. The calculations of absorbed dose depend upon both the properties of the radiation source and a biological model. Some of these data used are shown in Slide 5 which includes the distribution of this radiopharmaceutical in the body and the equilibrium dose constants for ^{99m}Tc.

The cumulated activity is dependent upon the biological behavior of the radiopharmaceutical. It depends upon such factors as the uptake of the radiopharmaceutical in the organs, its distribution within the individual organs, its biological retention and clearance. Dr. E. M. Smith, one of our consultants and a member of the MIRD Committee, supplied us with organ distributions and cumulated activity on several radiopharmaceuticals.

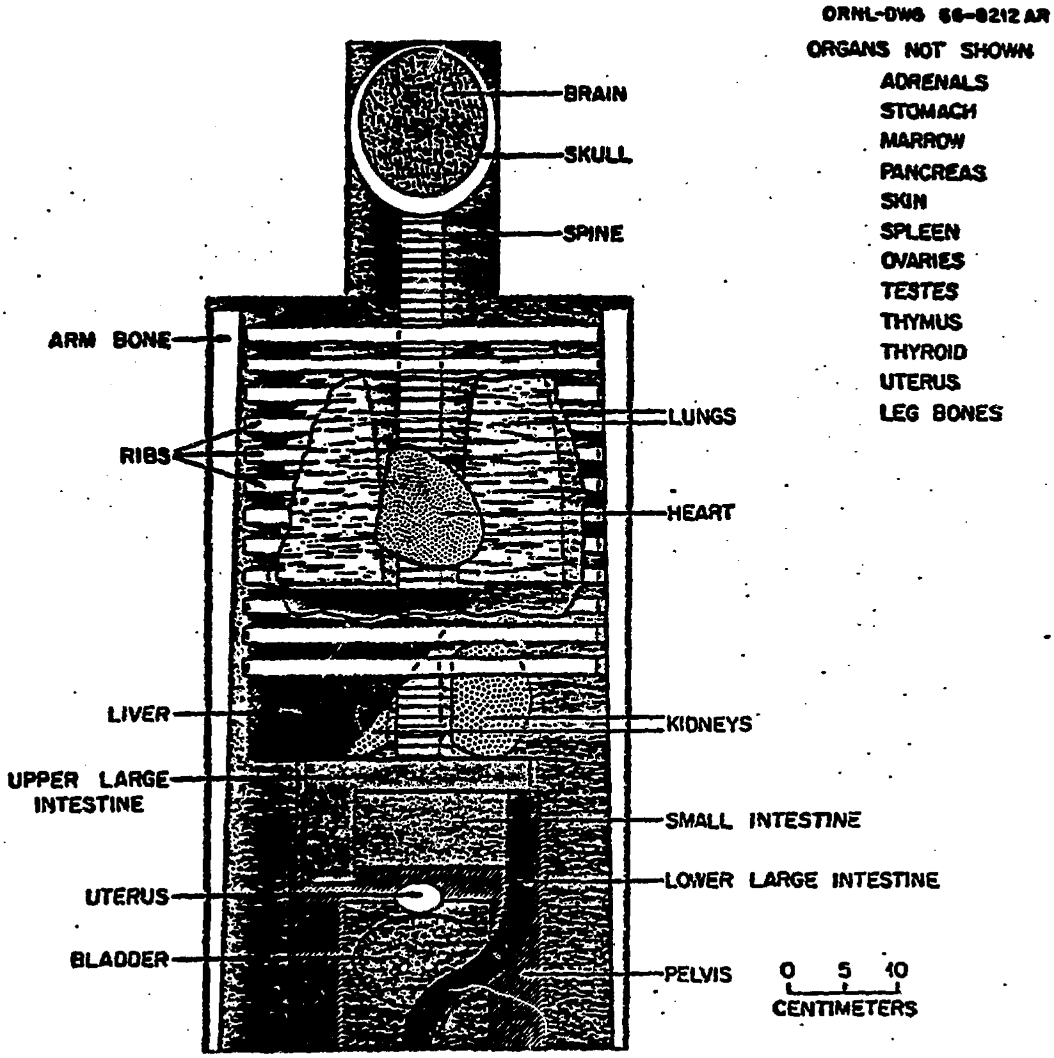
The equilibrium dose constants obtained from MIRD Pamphlet No. 10 were determined from the decay properties of ^{99m}Tc. Slide 6 shows how absorbed dose is calculated using the ^{99m}Tc decay data, cumulated activity, masses of target organs derived from the design of the phantom, and the absorbed fractions of penetrating x-ray or gamma-ray energy obtained from Monte Carlo calculations. The same absorbed fractions may be used to calculate S values, that is mean dose per unit accumulated activity expressed in units of rad per μCi-hr.

In considering the absorbed dose to a particular organ from an administered radiopharmaceutical, the dose will be the composite of exposures from all source organs as is illustrated in the next slide (Slide 7). For example, if you consider the ovaries, they receive 60% of their dose from the liver and 35% from the red bone marrow. It isn't inherently obvious that the red bone marrow would contribute 35% of the absorbed dose to the ovaries since it only accumulates 5% of the administered activity.

If one divides the absorbed fraction in the target organ by the mass of that organ, one obtains a specific absorbed fraction, i.e., fraction of absorbed energy per gram of a target organ. This allows one to compare fractions among various phantoms. Specific absorbed fractions have been calculated for target organs in the 1-year, 5-year, and adult phantoms using the liver as a source organ. These results are shown in Slide 8. Specific absorbed fractions are greater than a factor of 5 in the 1-year old than the adult for radiosensitive tissues such as the red bone marrow, gonads, and thyroid. We have made similar comparisons using different source organs and the results are analogous. This further confirms earlier determinations to this effect made at the Oak Ridge National Laboratory with similitude phantoms.

However, one must be cautioned about misinterpreting these results. For example, in nuclear medicine procedures, radiopharmaceuticals are administered for the most part, according to body weight; and an adult is over six times heavier than the 1-year old. Such a comparison will be more germane to population and nuclear siting studies where it would be useful to compare calculated dose commitments to children and adults in the same radioactive plume or radiation field.

To summarize, these pediatric phantoms were developed to be more representative of children. We didn't know when we started if significant differences would manifest themselves when the pediatric and similitude phantoms were compared. As was illustrated, there are significant differences and we now believe that calculations of absorbed doses to children will be more meaningful.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ORGANS NOT SHOWN
ADRENALS
STOMACH
MARROW
PANCREAS
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OVARIES
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THYROID
UTERUS
LEG BONES
BRAIN
SKULL
SPINE
ARM BONE
LUNGS
RIBS
HEART
LIVER
KIDNEYS
UPPER LARGE INTESTINE
SMALL INTESTINE
LOWER LARGE INTESTINE
UTERUS
BLADDER
PELVIS
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CENTIMETERS

SLIDE 1

SLIDE 2

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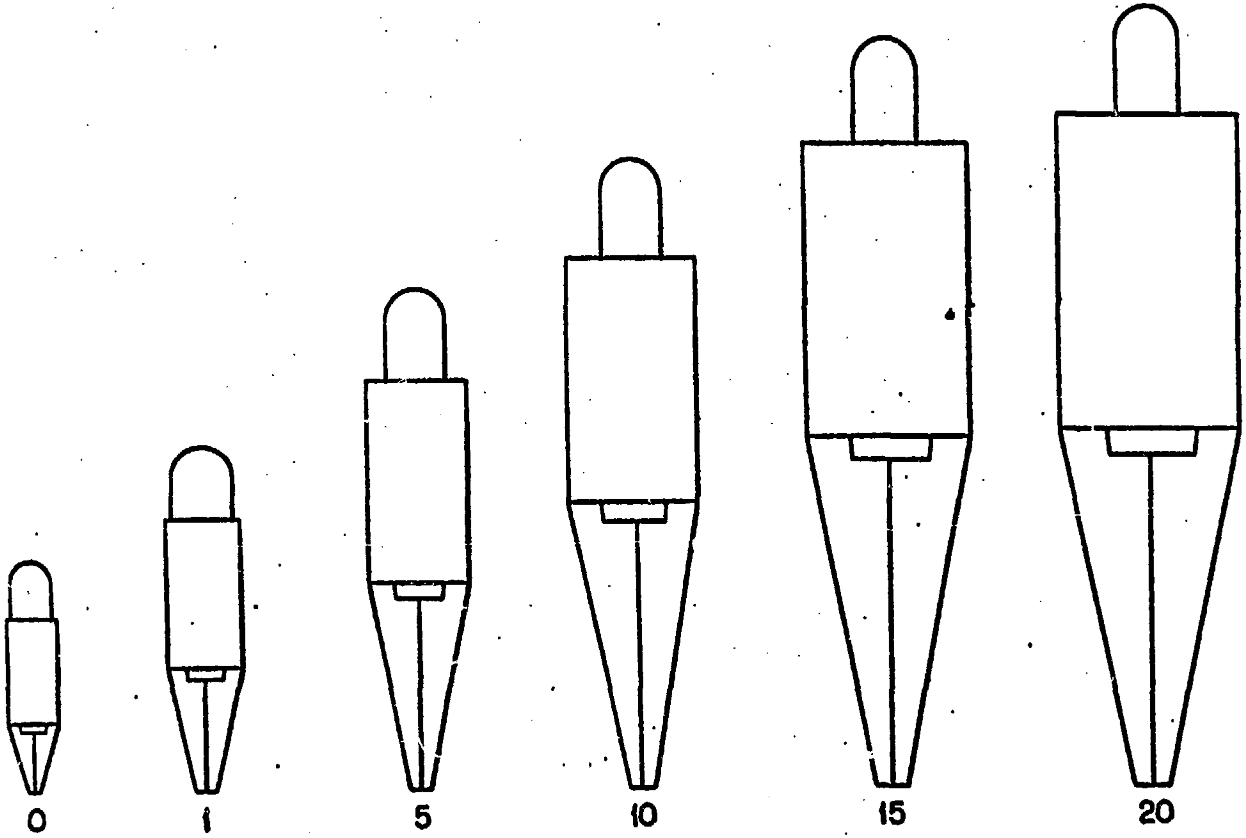
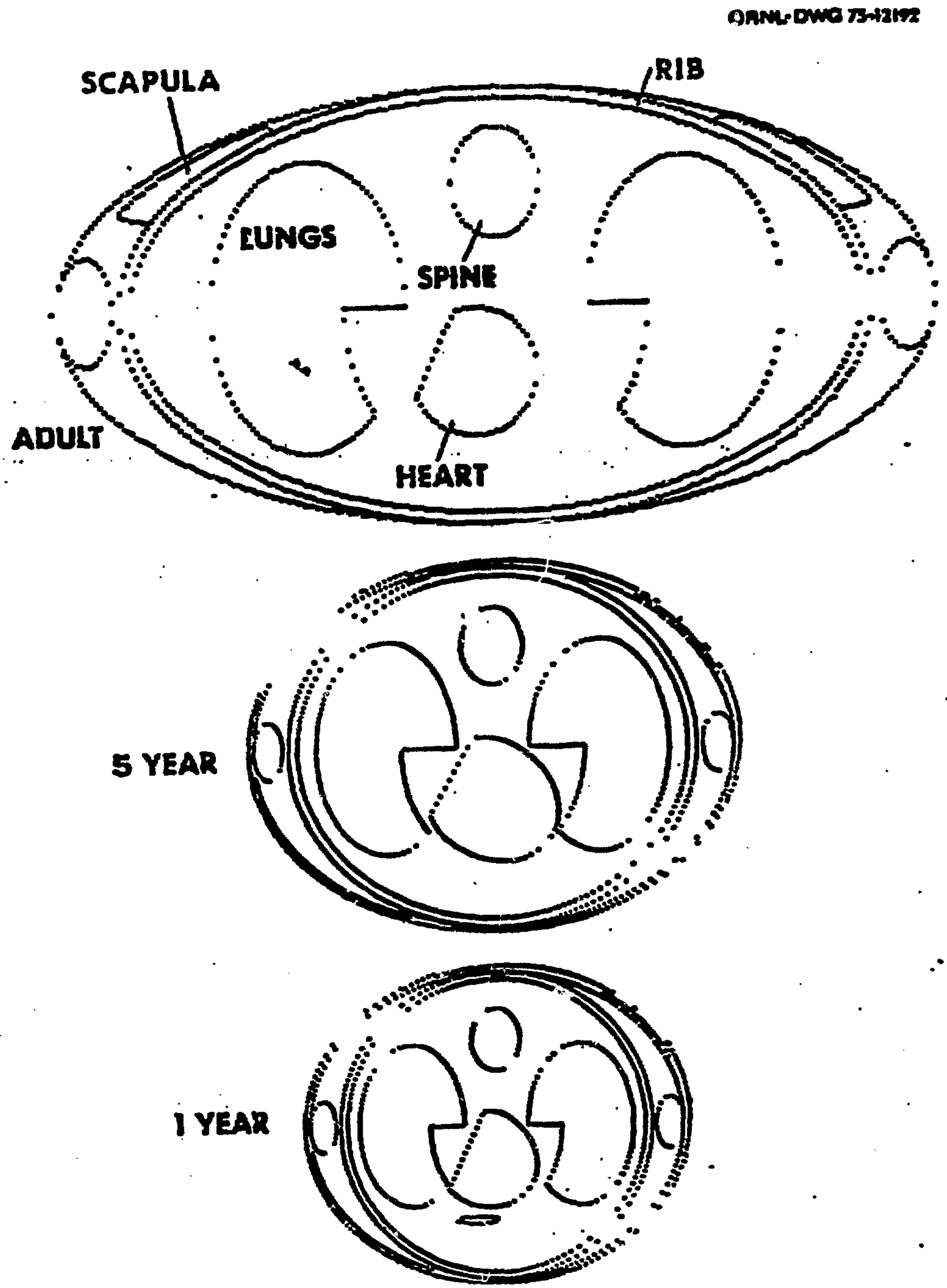


Relative Size of Phantoms for 0, 1, 5, 10, 15, and 20 Years.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SCAPULA
RIB
LUNGS
SPINE
HEART
ADULT
5 YEAR
1 YEAR

SLIDE 3

SLIDE 4

COMPARISON OF ABSORBED DOSES FROM ^{99M}Tc

ONE-YEAR OLD PEDIATRIC PHANTOM COMPARED WITH ONE-YEAR OLD SIMILITUDE PHANTOM

TARGET ORGANS	SOURCE ORGANS: LIVER	SOURCE ORGANS: RED BONE MARROW	SOURCE ORGANS: BLADDER CONTENTS
	(NUMBERS REPRESENT PERCENT DIFFERENCE)		
OVARIES	12	37	150
TESTES	8	50	51
KIDNEYS	24	41	61
LIVER	10	16	95
SKELETON	- 13	- 7	22
RED MARROW	88	0.5	- 13
THYROID	- 75	---	---
TOTAL BODY	10	14	14

Slide 5 (In Revision)

DISTRIBUTION OF SULFUR COLLOID

ORGAN	FRACTION OF ADMINISTERED ACTIVITY
LIVER	0.85
SPLEEN	0.07
RED MARROW	0.05
TOTAL BODY	0.03

TECHNETIUM-99M

PENETRATING RADIATION	EQUILIBRIUM DOSE CONSTANTS
GAMMA 1	.0000
GAMMA 2	.2630
GAMMA 3	.0001
ALPHA-1 X-RAY	.0017
ALPHA-2 X-RAY	.0008
BETA-1 X-RAY	.0004

SLIDE 6

CALCULATION OF ABSORBED DOSE FROM A RADIOPHARMACEUTICAL IN SOURCE ORGAN S TO TARGET ORGAN T

$$D(T \leftarrow S) = \frac{\tilde{A}_S}{M_T} \sum_i \Delta_i \phi_i (T \leftarrow S) \quad \text{RADS}$$

D IS ABSORBED DOSE FROM SOURCE ORGAN TO TARGET ORGAN

$\tilde{A}$ IS CUMULATED ACTIVITY (μCi-h) IN SOURCE ORGAN

M_T IS MASS OF TARGET ORGAN (g)

i IS 1 TO NUMBER OF PENETRATING RADIATIONS

Δ_i ARE EQUILIBRIUM DOSE CONSTANTS (g-rad/μCi-h)

ϕ_i ARE ABSORBED FRACTIONS

SLIDE 7

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ABSORBED DOSE TO THE SELECTED ORGANS IN THE ONE-YEAR OLD PHANTOM PER μCi OF ADMINISTERED ACTIVITY OF ^{99m}Tc-SULFUR COLLOID

Target Organs	Source Organs				Total Dose to the Target Organs (rads/μCi)
	Liver	Spleen	Red Marrow	Total Body	
Liver	5.806E-04	5.298E-06	2.010E-06	1.766E-06	5.897E-04
Ovaries	2.671E-05	1.270E-06	1.604E-05	1.804E-06	4.582E-05
Red Marrow	5.734E-05	6.464E-06	2.155E-05	2.242E-06	8.760E-05
Spleen	5.820E-05	2.657E-04	2.186E-06	1.761E-06	3.278E-04
Testes	1.130E-05	1.526E-07	3.125E-06	2.092E-06	1.667E-05
Thymus	3.082E-05	2.019E-06	1.399E-07	1.708E-06	3.469E-05
Thyroid	1.289E-05	5.846E-07	---	2.015E-06	1.549E-05
Total Body	5.371E-05	4.540E-06	3.228E-06	1.571E-06	6.305E-05

SLIDE 8

SPECIFIC ABSORBED FRACTIONS (x $10^6 g^{-1}$) IN VARIOUS TARGET ORGANS FROM ^{99M}Tc UNIFORMLY DISTRIBUTED IN THE LIVER IN THREE PHANTOMS

TARGET ORGAN	PHANTOM AGE		
	1 YEAR	5 YEAR	ADULT
OVARIES	27	14	5.8
TESTES	5.7	0.8	0.2
KIDNEYS	40	24	14
LIVER	297	186	90
LUNGS	29	17	7
RED MARROW	29	17	5
SKELETON	13	9	3.5
THYROID	6.6	0.9	0.2
TOTAL BODY	27	17	6