COMPARATIVE ANALYSIS OF DOSIMETRY PARAMETERS FOR NUCLEAR MEDICINE

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ABSTRACT

For years many have employed the concept of "total-body dose" or "whole-body dose," i.e., the total energy deposited in the body divided by the mass of the body, when evaluating the risks of different nuclear medicine procedures. The effective dose equivalent (H_E), first described in ICRP Publication 26, has been accepted by some as a better quantity to use in evaluating the total risk of a procedure, but its use has been criticized by others primarily because the tissue weighting factors were intended for use in the radiation worker, rather than the nuclear medicine patient population. Nevertheless, in ICRP Publication 52, the ICRP has suggested that the H_E may be used in nuclear medicine. The ICRP also has published a compendium of dose estimates, including H_E values, for various nuclear medicine procedures at various ages in ICRP Publication 53. The effective dose (E) of ICRP Publication 60 is perhaps more suitable for use in nuclear medicine, with tissue weighting factors based on the entire population. Other comparisons of H_E and E have been published. We have used the program MIRDOSE 3.1 to compute total-body dose, H_E, and E for 62 radiopharmaceutical procedures, based on the best current biokinetic data available. As found by other investigators, the average ratio of E to H_E is about 0.9, with a relatively narrow range from 0.48 to 1.77. The ratio of E to total-body dose, however, ranges from 1.1 to almost 100. In children, the ratio of E to H_E was 0.92, with a standard deviation of 0.32. The ratio of E to total-body dose varied from 1.0 to 166. All ratios greater than 10 occur for the iodines; the values for most Tc-99m agents are greater than 2.0. In view of the nonuniform distributions of most radiopharmaceuticals, we believe the total-body dose is not a useful concept, and should be replaced by the effective dose. In those countries that have not as yet adopted the ICRP 60 methodology, the effective dose equivalent should be used in the interim.

INTRODUCTION

For years many physicians and physicists have employed the concept of "total-body dose" or "whole-body dose," i.e., the total energy deposited in the body divided by the total mass of the body, in evaluating the risks of different nuclear medicine procedures. Although this concept has been considered useful for comparing doses received from different procedures, it does not take into account the typical nonuniformity in dose distribution among the several body organs. The effective dose equivalent (H_E), first described in ICRP Publication 26 (1), has been accepted by some as a better quantity to use in evaluating the total risk of a procedure, but its use has been criticized by

others primarily because the tissue weighting factors were intended for use with the population of radiation workers, rather than of nuclear medicine patients (2). Nevertheless, the ICRP has suggested in Publication 52 (3) that the H_E may be used in nuclear medicine, and provided in Publication 53 (4) a compendium of dose estimates, including H_E values, for various nuclear medicine procedures undergone at various ages. The effective dose (E) of ICRP Publication 60 (5) is perhaps more suitable for use in nuclear medicine, with tissue weighting factors based on the entire population.

Comparisons of H_E and E for adults have previously been published (6). The pediatric phantom series of Cristy and Eckerman (7) and the adult female phantom, published in conjunction with the pregnant woman phantom series (8), permits extension of this previous study to other populations. In this work, we will compare total-body dose to both H_E and E for adults (men and women) and children of various ages, using available biokinetic models for a large number of radiopharmaceutical procedures.

METHODS

We have used the program MIRDOSE 3.1 (9) to compute total-body dose, H_E and E for 62 radiopharmaceutical procedures, involving 19 different radionuclides, based on the best current biokinetic data available. The MIRDOSE software permits the use of organ residence times (10) with phantoms representing the adult male, adult female, and children of various ages, from newborn through 15-year-old. The biokinetic models have been taken from a number of different sources. Many are described in a recent compendium of internal dose estimates for radiopharmaceuticals (11), however, many others are based on internal data at the Radiation Internal Dose Information Center (RIDIC) in Oak Ridge. A full description of the assumptions in these models is outside of the scope of this article. None of the biokinetic models are specific to a particular gender or age group, as no such data, in complete form, are currently available. The best biokinetic model for an agent was used to obtain residence times that were applied to all of the phantoms. After calculation of the total-body dose, H_E and E, ratios of these quantities were also calculated.

RESULTS

The computed values of total-body dose, H_E and E are listed in Table 1, for both the adult female and adult male phantoms. Ratios of total-body dose to H_E and E are shown in Table 2. Total-body dose, H_E and E and ratios of these quantities for children are listed in Table 3. In addition, a comparison of many of the values of H_E calculated by MIRDOSE were compared to the same values reported in ICRP 53, for the different pediatric age groups and the adult male; this comparison is summarized in Table 4.

Abbreviations used in Tables 1-3:

Alb Mcrsph - albumin microspheres
Bladder Inf - infusion into urinary bladder
Brthld - breathhold
Dis - Diseased subjects
DISIDA - disofenin (iminodiacetic acid derivative)
DMSA - dimercaptosuccinic acid
DTPA - diethylentriaminpentaacetic acid
ECD - ethylene cystate dimer
FDG - fluorodeoxyglucose
Flsh - flushing dose administered
HDP - hydroxymethylene diphosphonate
Heat - heat treated
HEDP - hydroxyethylidene diphosphonate
HMPAO - hexamethylpropyleneamineoxine
HSA - human serum albumin
Hippuran - iodohippurate sodium
i.v. - intravenous
IMP - iodoamphetamine
MAA - macroaggregated albumin
MAG3 - mercaptoacetylglycylglycylglycine
MDP - methylene diphosphonate
mIBG - metaiodobenzylguanidine
MIBI - methoxyisobutyl isonitrile
Na2PO4 - sodium phosphate
NaF - sodium fluoride
NaI - sodium iodide
NH3 - ammonia
Nor - normal subjects
Nrml - Normal subjects
PA - percutaneous anemia subjects
PYP - pyrophosphate
RBC - red blood cells
Rebreath - rebreathing
Rt Hrt - right heart study
Slfr Cld - sulfur colloid
WBC- white blood cells

Table 1
Computed Values of Total-body Dose, H_E and E for Adult Females and Males
(Total-body Doses are given as mGy/MBq, H_E and E are mSv/MBq)

	FEMALES			MALES		
Pharmaceutical	Total-Body	H_E	E	Total-Body	H_E	E
Au-198 colloid	4.58E-01	1.72E+00	1.16E+00	3.59E-01	1.38E+00	9.14E-01
C-11 Tryptophane	3.60E-04	5.92E-04	5.03E-04	2.87E-03	5.16E-03	4.32E-03
C-11 Iomazenil	2.79E-03	1.54E-02	1.39E-02	2.20E-03	1.19E-02	1.06E-02
Co-57 B-12, Nor/flsh	1.91E+00	3.73E+00	2.90E+00	1.53E+00	2.94E+00	2.25E+00
Co-57 B-12, PA/flsh	2.68E-01	6.18E-01	5.99E-01	2.15E-01	5.00E-01	4.90E-01
Co-58 B-12, Nor/flsh	3.66E+00	7.08E+00	5.45E+00	2.96E+00	5.70E+00	4.35E+00
Co-58 B-12, PA/flsh	6.08E-01	1.61E+00	1.59E+00	4.93E-01	1.30E+00	1.30E+00
Co-60 B-12, Nor/flsh	5.61E+01	1.08E+02	8.01E+01	4.56E+01	8.67E+01	6.39E+01
Co-60 B-12, PA/flsh	7.49E+00	1.48E+01	1.24E+01	6.08E+00	1.19E+01	1.00E+01
F-18 FDG	1.51E-02	3.81E-02	3.10E-02	1.20E-02	2.98E-02	2.41E-02
F-18 NaF	1.10E-02	3.56E-02	3.10E-02	8.75E-03	2.70E-02	2.31E-02
Ga-67 Citrate	8.23E-02	1.23E-01	1.20E-01	6.62E-02	1.03E-01	1.00E-01
Hg-197 Chlormerodrin	3.84E-02	2.05E-01	1.13E-01	3.00E-02	1.81E-01	9.66E-02
I-123 Hippuran	3.52E-03	3.39E-02	2.90E-02	2.70E-03	2.38E-02	2.01E-02
I-123 IMP	1.43E-02	2.44E-02	2.34E-02	1.15E-02	1.91E-02	1.82E-02
I-123 mIBG	1.14E-02	2.56E-02	2.21E-02	9.12E-03	1.93E-02	1.66E-02
I-123 NaI	9.72E-03	1.47E-01	2.43E-01	8.03E-03	1.20E-01	2.00E-01
I-125 HSA	2.61E-01	3.89E-01	2.91E-01	2.07E-01	3.07E-01	2.29E-01
I-125 mIBG	2.93E-02	6.71E-02	4.86E-02	2.28E-02	5.08E-02	3.63E-02
I-125 NaI	1.61E-01	7.62E+00	1.35E+01	1.32E-01	6.37E+00	1.13E+01
I-131 Hippuran	9.71E-03	1.35E-01	1.17E-01	7.27E-03	1.00E-01	8.58E-02

Table 1 (continued)
Computed Values of Total-body Dose, H_E and E for Adult Females and Males
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

	FEMALES			MALES		
Pharmaceutical	Total-Body	H_E	E	Total-Body	H_E	E
I-131 HSA	5.89E-01	1.30E+00	9.35E-01	4.68E-01	1.07E+00	7.43E-01
I-131 MAA	1.80E-01	6.35E-01	6.06E-01	1.41E-01	4.96E-01	4.72E-01
I-131 mIBG	1.03E-01	2.51E-01	1.95E-01	8.12E-02	1.95E-01	1.49E-01
I-131 NaI	2.32E-01	1.27E+01	2.24E+01	1.92E-01	1.04E+01	1.84E+01
I-131 Rose Bengal	1.02E-01	1.02E+00	1.33E+00	8.13E-02	9.02E-01	1.21E+00
In-111 DTPA	1.11E-02	5.75E-02	5.02E-02	8.75E-03	4.10E-02	3.56E-02
In-111 Platelets	1.92E-01	6.18E-01	3.95E-01	1.55E-01	5.13E-01	3.26E-01
In-111 RBC	1.80E-01	2.47E-01	2.24E-01	1.48E-01	2.04E-01	1.85E-01
In-111 WBC	2.04E-01	7.62E-01	4.88E-01	1.63E-01	6.38E-01	4.09E-01
In-111 Pentetreotide	3.77E-02	1.46E-01	1.03E-01	3.02E-02	1.18E-01	8.14E-02
Kr-81m	5.72E-06	3.35E-05	3.39E-05	4.42E-06	2.65E-05	2.65E-05
N-13 NH_3	1.99E-03	2.81E-03	2.56E-03	1.58E-03	2.22E-03	2.01E-03
P-32 Na_2PO_4	1.96E+00	2.40E+00	2.29E+00	1.51E+00	1.93E+00	1.80E+00
Tc-99m Alb Mcrsph	5.43E-03	1.78E-02	1.77E-02	4.30E-03	1.45E-02	1.45E-02
Tc-99m DISIDA	4.93E-03	3.00E-02	2.15E-02	3.99E-03	2.51E-02	1.78E-02
Tc-99m DMSA	4.76E-03	1.85E-02	1.07E-02	3.81E-03	1.62E-02	9.12E-03
Tc-99m DTPA - iv	2.85E-03	1.11E-02	9.66E-03	2.29E-03	8.19E-03	7.09E-03
Tc-99m DTPA Aerosol	2.20E-03	7.90E-03	7.50E-03	1.75E-03	6.06E-03	5.76E-03
Tc-99m glucoheptonate	3.36E-03	1.35E-02	1.00E-02	2.69E-03	1.04E-02	7.42E-03
Tc-99m HDP	4.20E-03	7.45E-03	6.07E-03	3.40E-03	6.12E-03	4.80E-03
Tc-99m HEDP	2.95E-03	7.86E-03	6.55E-03	2.37E-03	6.10E-03	4.96E-03
Tc-99m HMPAO	4.69E-03	1.68E-02	1.29E-02	3.78E-03	1.38E-02	1.09E-02
Tc-99m HSA	5.30E-03	9.59E-03	7.54E-03	4.28E-03	7.85E-03	6.21E-03
Tc-99m MAA	5.22E-03	1.62E-02	1.54E-02	4.12E-03	1.27E-02	1.20E-02
Tc-99m MAG3	2.04E-03	1.64E-02	1.40E-02	1.60E-03	1.18E-02	9.99E-03
Tc-99m MDP	3.27E-03	7.64E-03	6.19E-03	2.64E-03	6.08E-03	4.75E-03
Tc-99m MIBI/stress	4.65E-03	1.55E-02	1.31E-02	3.77E-03	1.27E-02	1.07E-02
Tc-99m MIBI/rest	5.26E-03	1.83E-02	1.63E-02	4.26E-03	1.49E-02	1.33E-02
Tc-99m Pertechnetate	3.94E-03	1.32E-02	1.40E-02	3.18E-03	1.06E-02	1.14E-02
Tc-99m PYP	4.12E-03	7.46E-03	6.31E-03	3.34E-03	6.03E-03	4.95E-03
Tc-99m RBC/in vitro	4.65E-03	9.19E-03	7.83E-03	3.75E-03	7.28E-03	6.11E-03
Tc-99m RBC/in vivo	4.95E-03	8.95E-03	7.59E-03	3.99E-03	7.17E-03	5.99E-03
Tc-99m RBC/heat	6.25E-03	5.55E-02	2.66E-02	4.94E-03	4.64E-02	2.24E-02
Tc-99m Slfr Cld/Nrml	6.24E-03	1.69E-02	1.03E-02	4.99E-03	1.36E-02	8.04E-03
Tc-99m Slfr Cld/Dis	6.11E-03	2.60E-02	1.59E-02	4.88E-03	2.16E-02	1.32E-02
Tc-99m Slfr Cld/Oral	5.28E-03	3.00E-02	2.88E-02	4.72E-03	2.77E-02	2.68E-02
Tc-99m Teboroxime	4.75E-03	1.49E-02	1.23E-02	3.86E-03	1.24E-02	1.00E-02
Tc-99m WBC	6.08E-03	2.39E-02	1.54E-02	4.87E-03	2.00E-02	1.29E-02
Tl-201 Chloride	6.79E-02	1.87E-01	1.65E-01	5.46E-02	3.16E-01	2.74E-01
Xe-127, 10 min brthld	2.22E-04	2.92E-04	2.92E-04	1.80E-04	2.36E-04	2.36E-04
Xe-133, 10 min brthld	2.59E-04	3.79E-04	3.86E-04	2.02E-04	2.98E-04	3.04E-04

Table 2
Ratios of H_E and E to Total-body Dose for Adult Females and Males

	FEMALES			MALES		
Pharmaceutical	H_E/TB	E/TB	E/H_E	H_E/TB	E/TB	E/H_E
Au-198 colloid	3.76	2.53	0.67	3.84	2.55	0.66
C-11 Tryptophane	1.6	1.40	0.85	1.80	1.51	0.84
C-11 Iomazenil	5.52	4.98	0.90	5.41	4.82	0.89
Co-57 B-12, Nor/flsh	1.95	1.52	0.78	1.92	1.47	0.77
Co-57 B-12, PA/flsh	2.31	2.24	0.97	2.33	2.28	0.98
Co-58 B-12, Nor/flsh	1.93	1.49	0.77	1.93	1.47	0.76
Co-58 B-12, PA/flsh	2.65	2.62	0.99	2.64	2.64	1.00
Co-60 B-12, Nor/flsh	1.93	1.43	0.74	1.90	1.40	0.74
Co-60 B-12, PA/flsh	1.98	1.66	0.84	1.96	1.64	0.84
F-18 FDG	2.52	2.05	0.81	2.48	2.01	0.81
F-18 NaF	3.24	2.82	0.87	3.09	2.64	0.86
Ga-67 Citrate	1.49	1.46	0.98	1.56	1.51	0.97
Hg-197 Chlormerodrin	5.34	2.94	0.55	6.03	3.22	0.53
I-123 Hippuran	9.63	8.24	0.86	8.81	7.44	0.84
I-123 IMP	1.71	1.64	0.96	1.66	1.58	0.95
I-123 mIBG	2.25	1.94	0.86	2.12	1.82	0.86
I-123 NaI	15.12	25.00	1.65	14.94	24.91	1.67
I-125 HSA	1.49	1.11	0.75	1.48	1.11	0.75
I-125 mIBG	2.29	1.66	0.72	2.23	1.59	0.71
I-125 NaI	47.33	83.85	1.77	48.26	85.61	1.77
I-131 Hippuran	13.90	12.05	0.87	13.76	11.80	0.86
I-131 HSA	2.21	1.59	0.72	2.29	1.59	0.69
I-131 MAA	3.53	3.37	0.95	3.52	3.35	0.95
I-131 mIBG	2.44	1.89	0.78	2.40	1.83	0.76
I-131 NaI	54.74	96.55	1.76	54.17	95.83	1.77
I-131 Rose Bengal	10.00	13.04	1.30	11.09	14.88	1.34
In-111 DTPA	5.18	4.52	0.87	4.69	4.07	0.87
In-111 Platelets	3.22	2.06	0.64	3.31	2.10	0.64
In-111 RBC	1.37	1.24	0.91	1.38	1.25	0.91
In-111 WBC	3.74	2.39	0.64	3.91	2.51	0.64
In-111 Pentetreotide	3.87	2.73	0.71	3.91	2.70	0.69
Kr-81m	5.86	5.93	1.01	6.00	6.00	1.00
N-13 NH_3	1.41	1.29	0.91	1.41	1.27	0.91
P-32 Na_2PO_4	1.22	1.17	0.95	1.28	1.19	0.93
Tc-99m Alb Mcrsph	3.28	3.26	0.99	3.37	3.37	1.00
Tc-99m DISIDA	6.09	4.36	0.72	6.29	4.46	0.71
Tc-99m DMSA	3.89	2.25	0.58	4.25	2.39	0.56
Tc-99m DTPA - iv	3.89	3.39	0.87	3.58	3.10	0.87
Tc-99m DTPA Aerosol	3.59	3.41	0.95	3.46	3.29	0.95
Tc-99m glucoheptonate	4.02	2.98	0.74	3.87	2.76	0.71
Tc-99m HDP	1.77	1.45	0.81	1.80	1.41	0.78
Tc-99m HEDP	2.66	2.22	0.83	2.57	2.09	0.81
Tc-99m HMPAO	3.58	2.75	0.77	3.65	2.88	0.79
Tc-99m HSA	1.81	1.42	0.79	1.83	1.45	0.79
Tc-99m MAA	3.10	2.95	0.95	3.08	2.91	0.94

Table 2 (continued)
Ratios of H_E and E to Total-body Dose for Adult Females and Males

	FEMALES			MALES		
Pharmaceutical	H_E/TB	E/TB	E/H_E	H_E/TB	E/TB	E/H_E
Tc-99m MAG3	8.04	6.86	0.85	7.38	6.24	0.85
Tc-99m MDP	2.34	1.89	0.81	2.30	1.80	0.78
Tc-99m MIBI/stress	3.33	2.82	0.85	3.37	2.84	0.84
Tc-99m MIBI/rest	3.48	3.10	0.89	3.50	3.12	0.89
Tc-99m Pertechnetate	3.35	3.55	1.06	3.33	3.58	1.08
Tc-99m PYP	1.81	1.53	0.85	1.81	1.48	0.82
Tc-99m RBC/in vitro	1.98	1.68	0.85	1.94	1.63	0.84
Tc-99m RBC/in vivo	1.81	1.53	0.85	1.80	1.50	0.84
Tc-99m RBC/heat	8.88	4.26	0.48	9.39	4.53	0.48
Tc-99m Slfr Cld/Nrml	2.71	1.65	0.61	2.73	1.61	0.59
Tc-99m Slfr Cld/Dis	4.26	2.60	0.61	4.43	2.70	0.61
Tc-99m Slfr Cld/Oral	5.68	5.45	0.96	5.87	5.68	0.97
Tc-99m Teboroxime	3.14	2.59	0.83	3.21	2.59	0.81
Tc-99m WBC	3.93	2.53	0.64	4.11	2.65	0.65
Tl-201 Chloride	2.75	2.43	0.88	5.79	5.02	0.87
Xe-127, 10 min brthld	1.32	1.32	1.00	1.31	1.31	1.00
Xe-133, 10 min brthld	1.46	1.49	1.02	1.48	1.50	1.02
AVERAGE:	5.27	6.13	0.88	5.34	6.19	0.87

Table 3
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
Ga-67 citrate						
0	0.885	1.28	1.16	1.446	1.311	0.906
1	0.372	0.538	0.487	1.446	1.309	0.905
5	0.203	0.32	0.304	1.576	1.498	0.950
10	0.129	0.205	0.197	1.589	1.527	0.961
15	0.0822	0.13	0.124	1.582	1.509	0.954
Kr-81m gas						
0	6.84E-05	4.64E-04	4.83E-04	6.784	7.061	1.041
1	2.77E-05	1.70E-04	1.76E-04	6.137	6.354	1.035
5	1.43E-05	8.71E-05	8.90E-05	6.091	6.224	1.022
10	8.99E-06	5.66E-05	5.75E-05	6.296	6.396	1.016
15	5.74E-06	3.96E-05	4.04E-05	6.899	7.038	1.020
I-123 mIBG						
0	0.114	0.173	0.147	1.518	1.289	0.850
1	0.0485	0.0771	0.0654	1.590	1.348	0.848
5	0.0266	0.0456	0.039	1.714	1.466	0.855
10	0.0171	0.0302	0.0257	1.766	1.503	0.851
15	0.0114	0.0248	0.0213	2.175	1.868	0.859

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
I-125 mIBG						
0	0.396	0.679	0.492	1.715	1.242	0.725
1	0.156	0.286	0.209	1.833	1.340	0.731
5	0.0787	0.153	0.112	1.944	1.423	0.732
10	0.0485	0.0971	0.0679	2.002	1.400	0.699
15	0.0295	0.0684	0.0485	2.319	1.644	0.709
I-131 mIBG						
0	1.27	2.44	1.84	1.921	1.449	0.754
1	0.51	1.04	0.707	2.039	1.386	0.680
5	0.266	0.588	0.399	2.211	1.500	0.679
10	0.166	0.379	0.254	2.283	1.530	0.670
15	0.106	0.282	0.197	2.660	1.858	0.699
I-123 NaI						
0	0.101	1.59	2.71	15.743	26.832	1.704
1	0.0433	1.11	1.91	25.635	44.111	1.721
5	0.0239	0.593	1.02	24.812	42.678	1.720
10	0.0149	0.278	0.473	18.658	31.745	1.701
15	0.0101	0.188	0.317	18.614	31.386	1.686
I-125 NaI						
0	2.44	86.7	153	35.533	62.705	1.765
1	0.953	63.1	111	66.212	116.474	1.759
5	0.488	33.7	59.6	69.057	122.131	1.769
10	0.291	15.5	27.3	53.265	93.814	1.761
15	0.174	10.2	18	58.621	103.448	1.765
I-131 NaI						
0	3.05	161	283	52.787	92.787	1.758
1	1.24	116	206	93.548	166.129	1.776
5	0.646	60.5	107	93.653	165.635	1.769
10	0.394	26.7	47.1	67.766	119.543	1.764
15	0.245	17.2	30.4	70.204	124.082	1.767
I-123 Hippuran						
0	0.00894	0.064	0.0513	7.159	5.738	0.802
1	0.00381	0.0274	0.0219	7.192	5.748	0.799
5	0.00355	0.0296	0.0245	8.338	6.901	0.828
10	0.00228	0.0195	0.0163	8.553	7.149	0.836
15	0.00343	0.0302	0.0256	8.805	7.464	0.848
I-131 Hippuran						
0	0.0259	0.295	0.236	11.390	9.112	0.800
1	0.00983	0.116	0.0934	11.801	9.502	0.805
5	0.00849	0.124	0.104	14.605	12.250	0.839
10	0.00548	0.0801	0.0669	14.617	12.208	0.835
15	0.00952	0.129	0.111	13.550	11.660	0.860

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
In-111 Platelets						
0	1.82	6.47	3.96	3.555	2.176	0.612
1	0.808	2.71	1.68	3.354	2.079	0.620
5	0.448	1.56	0.962	3.482	2.147	0.617
10	0.293	1.02	0.637	3.481	2.174	0.625
15	0.19	0.687	0.426	3.616	2.242	0.620
In-111 RBC						
0	1.76	2.39	2.11	1.358	1.199	0.883
1	0.776	1.05	0.938	1.353	1.209	0.893
5	0.431	0.591	0.527	1.371	1.223	0.892
10	0.275	0.388	0.349	1.411	1.269	0.899
15	0.18	0.26	0.232	1.444	1.289	0.892
In-111 WBC						
0	1.82	8.52	5.57	4.681	3.060	0.654
1	0.819	3.38	2.17	4.127	2.650	0.642
5	0.459	1.91	1.19	4.161	2.593	0.623
10	0.308	1.24	0.773	4.026	2.510	0.623
15	0.202	0.836	0.522	4.139	2.584	0.624
Kr-81m iv						
0	3.33E-05	5.73E-04	1.16E-03	17.207	34.835	2.024
1	1.44E-05	1.79E-04	3.55E-04	12.431	24.653	1.983
5	7.98E-06	9.04E-05	1.76E-04	11.328	22.055	1.947
10	5.17E-06	5.36E-05	1.02E-04	10.368	19.729	1.903
15	3.32E-06	3.70E-05	7.09E-05	11.145	21.355	1.916
Kr-81m Rt Hrt						
0	4.14E-05	2.51E-04	1.24E-04	6.063	2.995	0.494
1	1.74E-05	1.14E-04	4.80E-05	6.552	2.759	0.421
5	9.19E-06	6.27E-05	2.51E-05	6.823	2.731	0.400
10	5.97E-06	4.04E-05	1.63E-05	6.767	2.730	0.403
15	3.92E-06	2.74E-05	1.17E-05	6.990	2.985	0.427
Tc-99m Alb Mcrsph						
0	0.0495	0.198	0.205	4.000	4.141	1.035
1	0.0223	0.0799	0.083	3.583	3.722	1.039
5	0.0124	0.0433	0.0445	3.492	3.589	1.028
10	0.00805	0.0282	0.0284	3.503	3.528	1.007
15	0.00543	0.0197	0.0198	3.628	3.646	1.005

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Tc-99m Bladder Inf						
0	9.56E-04	9.51E-03	8.18E-03	9.948	8.556	0.860
1	4.48E-04	4.22E-03	3.59E-03	9.420	8.013	0.851
5	2.68E-04	2.36E-03	2.00E-03	8.806	7.463	0.847
10	1.79E-04	1.60E-03	1.36E-03	8.939	7.598	0.850
15	1.35E-04	1.09E-03	9.27E-04	8.074	6.867	0.850
Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
Tc-99m DISIDA						
0	0.0398	0.347	0.217	8.719	5.452	0.625
1	0.0188	0.157	0.0953	8.351	5.069	0.607
5	0.011	0.072	0.0537	6.545	4.882	0.746
10	0.00723	0.0453	0.0346	6.266	4.786	0.764
15	0.00497	0.031	0.0228	6.237	4.588	0.735
Tc-99m DMSA						
0	0.043	0.159	0.0861	3.698	2.002	0.542
1	0.0193	0.0671	0.037	3.477	1.917	0.551
5	0.0109	0.039	0.0221	3.578	2.028	0.567
10	0.00692	0.0269	0.0151	3.887	2.182	0.561
15	0.00472	0.0197	0.0112	4.174	2.373	0.569
Tc-99m DTPA						
0	0.019	0.0335	0.03	1.763	1.579	0.896
1	0.00843	0.015	0.0136	1.779	1.613	0.907
5	0.00515	0.012	0.0107	2.330	2.078	0.892
10	0.00331	0.0081	0.00723	2.447	2.184	0.893
15	0.00282	0.0103	0.00895	3.652	3.174	0.869
Tc-99m DTPA Aerosol						
0	0.0164	0.0492	0.0521	3.000	3.177	1.059
1	0.00741	0.0207	0.0217	2.794	2.928	1.048
5	0.00446	0.0133	0.0133	2.982	2.982	1.000
10	0.0029	0.00884	0.00873	3.048	3.010	0.988
15	0.00219	0.00797	0.00766	3.639	3.498	0.961
Tc-99m ECD						
0	0.0214	0.0799	0.056	3.734	2.617	0.701
1	0.00988	0.0371	0.026	3.755	2.632	0.701
5	0.00651	0.0228	0.0181	3.502	2.780	0.794
10	0.00425	0.0146	0.0117	3.435	2.753	0.801
15	0.0034	0.0141	0.0115	4.147	3.382	0.816

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
Tc-99m HDP						
0	0.0388	0.0797	0.0693	2.054	1.786	0.870
1	0.0174	0.0338	0.0283	1.943	1.626	0.837
5	0.00971	0.0187	0.015	1.926	1.545	0.802
10	0.00628	0.0114	0.00924	1.815	1.471	0.811
15	0.00417	0.00728	0.00591	1.746	1.417	0.812
Tc-99m HEDP						
0	0.0265	0.0703	0.0596	2.653	2.249	0.848
1	0.0119	0.0307	0.0258	2.580	2.168	0.840
5	0.00671	0.0172	0.0142	2.563	2.116	0.826
10	0.00434	0.0112	0.00934	2.581	2.152	0.834
15	0.00292	0.0075	0.0062	2.568	2.123	0.827
Tc-99m HMPAO						
0	0.0372	0.16	0.108	4.301	2.903	0.675
1	0.0171	0.0755	0.0544	4.415	3.181	0.721
5	0.0104	0.0379	0.0318	3.644	3.058	0.839
10	0.00681	0.0234	0.019	3.436	2.790	0.812
15	0.00469	0.0175	0.0138	3.731	2.942	0.789
Tc-99m MAA						
0	0.0478	0.172	0.171	3.598	3.577	0.994
1	0.0215	0.0695	0.0681	3.233	3.167	0.980
5	0.0119	0.0378	0.0365	3.176	3.067	0.966
10	0.00778	0.0252	0.0242	3.239	3.111	0.960
15	0.00523	0.0177	0.017	3.384	3.250	0.960
Tc-99m MAG3						
0	0.00476	0.0323	0.0265	6.786	5.567	0.820
1	0.00219	0.0142	0.0117	6.484	5.342	0.824
5	0.0021	0.0151	0.0126	7.190	6.000	0.834
10	0.00138	0.0103	0.0086	7.464	6.232	0.835
15	0.002	0.0148	0.0126	7.400	6.300	0.851
Tc-99m MDP						
0	0.0296	0.0747	0.0631	2.524	2.132	0.845
1	0.0133	0.032	0.0263	2.406	1.977	0.822
5	0.00747	0.0178	0.0142	2.383	1.901	0.798
10	0.00484	0.0113	0.00904	2.335	1.868	0.800
15	0.00324	0.00735	0.0059	2.269	1.821	0.803
Tc-99m MIBI						
0	0.0382	0.138	0.139	3.613	3.639	1.007
1	0.018	0.0653	0.0654	3.628	3.633	1.002
5	0.012	0.0443	0.0418	3.692	3.483	0.944
10	0.00791	0.0291	0.0264	3.679	3.338	0.907
15	0.00527	0.0189	0.0169	3.586	3.207	0.894

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
Tc-99m Pertechnetate						
0	0.0392	0.117	0.144	2.985	3.673	1.231
1	0.0176	0.0533	0.0619	3.028	3.517	1.161
5	0.0101	0.0307	0.0349	3.040	3.455	1.137
10	0.00654	0.0192	0.0224	2.936	3.425	1.167
15	0.00456	0.0144	0.0156	3.158	3.421	1.083
Tc-99m PYP						
0	0.0382	0.0749	0.066	1.961	1.728	0.881
1	0.0171	0.0324	0.0278	1.895	1.626	0.858
5	0.00955	0.0179	0.015	1.874	1.571	0.838
10	0.00616	0.0112	0.00948	1.818	1.539	0.846
15	0.00409	0.00728	0.00614	1.780	1.501	0.843
Tc-99m RBC Heat						
0	0.0567	0.653	0.304	11.517	5.362	0.466
1	0.0255	0.259	0.122	10.157	4.784	0.471
5	0.0143	0.147	0.0697	10.280	4.874	0.474
10	0.00932	0.0967	0.0459	10.376	4.925	0.475
15	0.00617	0.0643	0.0305	10.421	4.943	0.474
Tc-99m RBC in vitro						
0	0.0433	0.0833	0.0709	1.924	1.637	0.851
1	0.0193	0.0369	0.0314	1.912	1.627	0.851
5	0.0108	0.0206	0.0174	1.907	1.611	0.845
10	0.00697	0.0138	0.0118	1.980	1.693	0.855
15	0.00462	0.00949	0.008	2.054	1.732	0.843
Tc-99m RBC in vivo						
0	0.0464	0.0821	0.0698	1.769	1.504	0.850
1	0.0207	0.0364	0.031	1.758	1.498	0.852
5	0.0116	0.0204	0.0172	1.759	1.483	0.843
10	0.00745	0.0136	0.0116	1.826	1.557	0.853
15	0.00493	0.00936	0.00786	1.899	1.594	0.840
Tc-99m Slfr Cld normal						
0	0.0568	0.152	0.0925	2.676	1.629	0.609
1	0.0256	0.0683	0.0421	2.668	1.645	0.616
5	0.0143	0.0385	0.0233	2.692	1.629	0.605
10	0.00971	0.026	0.0157	2.678	1.617	0.604
15	0.00623	0.0175	0.0103	2.809	1.653	0.589
Tc-99m Slfr Cld Dis						
0	0.0547	0.308	0.189	5.631	3.455	0.614
1	0.0246	0.121	0.0738	4.919	3.000	0.610
5	0.0139	0.0671	0.04	4.827	2.878	0.596
10	0.00922	0.0435	0.0259	4.718	2.809	0.595
15	0.00607	0.029	0.0172	4.778	2.834	0.593

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_E/TB	E/TB	E/H_E
Tc-99m Slfr Cld oral						
0	0.0223	0.197	0.225	8.834	10.090	1.142
1	0.0125	0.0981	0.118	7.848	9.440	1.203
5	0.0115	0.0773	0.0804	6.722	6.991	1.040
10	0.00802	0.0504	0.049	6.284	6.110	0.972
15	0.00533	0.0319	0.0313	5.985	5.872	0.981
Tc-99m WBC						
0	0.0536	0.296	0.198	5.522	3.694	0.669
1	0.0242	0.113	0.0741	4.669	3.062	0.656
5	0.0137	0.0616	0.0391	4.496	2.854	0.635
10	0.0091	0.0396	0.0248	4.352	2.725	0.626
15	0.00604	0.0263	0.0165	4.354	2.732	0.627
Tl-201 Chloride						
0	0.795	4.03	3.65	5.069	4.591	0.906
1	0.33	2.28	2.08	6.909	6.303	0.912
5	0.175	1.5	1.34	8.571	7.657	0.893
10	0.11	1.16	1.01	10.545	9.182	0.871
15	0.0684	0.293	0.264	4.284	3.860	0.901
Xe-133 Rt Hrt						
0	0.00236	0.0179	0.0177	7.585	7.500	0.989
1	8.98E-04	0.00661	0.00631	7.361	7.027	0.955
5	4.48E-04	3.32E-03	3.13E-03	7.411	6.987	0.943
10	2.71E-04	2.13E-03	2.01E-03	7.860	7.417	0.944
15	1.62E-04	1.46E-03	1.40E-03	9.012	8.642	0.959
Xe-133 brthld						
0	2.09E-03	3.57E-03	3.66E-03	1.708	1.751	1.025
1	7.90E-04	1.32E-03	1.35E-03	1.671	1.709	1.023
5	3.94E-04	6.55E-04	6.71E-04	1.662	1.703	1.024
10	2.38E-04	4.09E-04	4.19E-04	1.718	1.761	1.024
15	1.41E-04	2.65E-04	2.73E-04	1.879	1.936	1.030
Xe-133 5 min rebreathing						
0	1.31E-02	1.41E-02	1.41E-02	1.076	1.076	1.000
1	4.97E-03	5.31E-03	5.33E-03	1.068	1.072	1.004
5	2.48E-03	2.65E-03	2.65E-03	1.069	1.069	1.000
10	1.49E-03	1.61E-03	1.62E-03	1.081	1.087	1.006
15	8.86E-04	9.88E-04	8.86E-04	1.115	1.000	0.897
Xe-133 10 min rebreathing						
0	0.0215	0.0217	0.0217	1.009	1.009	1.000
1	0.00816	0.00823	0.00822	1.009	1.007	0.999
5	0.00407	0.0041	0.00409	1.007	1.005	0.998
10	0.00245	0.00249	0.00249	1.016	1.016	1.000
15	0.00145	0.00151	0.00151	1.041	1.041	1.000

Table 3 (continued)
Computed Values of Total-body Dose, H_E and E, and Ratios for Children
(Total-body doses are given as mGy/MBq, H_E and E are mSv/MBq)

Age (y)	TB	H_E	E	H_ETB	E/TB	E/H_E
Xe-127 brthld						
0	1.28E-03	1.76E-03	1.77E-03	1.375	1.383	1.006
1	5.55E-04	7.58E-04	7.54E-04	1.366	1.359	0.995
5	3.02E-04	4.13E-04	4.12E-04	1.368	1.364	0.998
10	1.93E-04	2.71E-04	2.70E-04	1.404	1.399	0.996
15	1.25E-04	1.84E-04	1.83E-04	1.472	1.464	0.995
Xe-127 5 min rebreathing						
0	8.22E-03	8.99E-03	8.98E-03	1.094	1.092	0.999
1	3.56E-03	3.97E-03	3.95E-03	1.115	1.110	0.995
5	1.94E-03	2.18E-03	2.18E-03	1.124	1.124	1.000
10	1.24E-03	1.42E-03	1.42E-03	1.145	1.145	1.000
15	7.99E-04	9.47E-04	9.45E-04	1.185	1.183	0.998
Xe-127 10 min rebreathing						
0	0.0132	0.0141	0.014	1.068	1.061	0.993
1	5.71E-03	6.23E-03	6.20E-03	1.091	1.086	0.995
5	3.12E-03	3.43E-03	3.42E-03	1.099	1.096	0.997
10	1.99E-03	2.23E-03	2.23E-03	1.121	1.121	1.000
15	1.28E-03	1.49E-03	1.48E-03	1.164	1.156	0.993

Table 4
Ratios of MIRDOSE 3.1 to ICRP 53 Values of H_E

Phantom	MIRDOSE/ICRP
1-year-old	0.89 +/- 0.27
5-year-old	0.92 +/- 0.18
10-year-old	0.92 +/- 0.16
15-year-old	1.01 +/- 0.20
Adult	1.00 +/- 0.20
Mean	0.95 +/- 0.05

DISCUSSION

As reported by Johansson et al. (6), the average ratio of E to H_E for adults is about 0.8, with a relatively narrow spread from 0.48 to 1.77. The ratio of E to total-body dose in adults, however, ranges from 1.1 to almost 100. All ratios greater than 10 occur for the iodines; the values for Tc-99m agents fall between 1.4 and 6.9; it is of interest to note that Tc-99m and the iodines are the most widely used radiopharmaceuticals. In children, the ratio of E to H_E was 0.92, with a standard deviation of 0.32. The ratio of E to total-body dose varied from 1.0 to 166. Again, the largest ratios were observed in the iodine-labeled compounds.

Thus, a very different view of risk will be obtained by using the total-body dose versus either the value of E or H_E for a procedure. In view of the nonuniform distributions of most

radiopharmaceuticals, we believe the total-body dose is not a useful concept, and should be replaced by the effective dose. In those countries that have not as yet adopted the ICRP 60 (5) methodology, the effective dose equivalent should be used in the interim.

It is essential, however, to recognize the limitations on the use of these quantities. First, it is always important to study the actual organ doses. The calculation of E and H_E, involving multiplying individual organ doses by risk weighting factors and adding up individual contributions into a single value, necessarily causes a loss of information about the doses to different organs. It is important to remember also that the E and H_E are theoretical quantities; no organ or system, including the total body, actually received the value calculated. A second limitation on the use of the E or H_E is that it must never be used in situations involving radiation therapy. The risk weighting factors relate only to the induction of cancer or hereditary disease, and do not give any information about organ radiosensitivity to deterministic effects. Thirdly, it should be remembered that the E and H_E should always be applied to *populations*, never individuals. They have some usefulness in studying differences between procedures when used in large populations, or in estimating risks, but should not be used to calculate risks to individuals from specific procedures.

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QUESTIONS

Rao: What is effective dose? It sounds as if it gives the effect, while it does not. Another point to be made is that when a somewhat higher dose is delivered to an organ with a radionuclide whose effective half-life is long compared to a short-lived radionuclide, it does not necessarily follow that the damage from the radionuclide with a long effective half-life is greater than that from the one with a short effective half-life, because of dose-rate effects.

Toohey: Effective dose is a construct developed by the ICRP to relate the risk of stochastic effects from highly nonuniform internal dose to those observed from more uniform, external whole-body radiation dose. The tissue weighting factors give the relative sensitivity of each organ or tissue to stochastic effects. Our position is that because the concept of effective dose takes into account the nonuniform irradiation of internal organs from any given radiopharmaceutical, as well as the sensitivity of each organ to stochastic effects, it is a more useful concept than "whole-body dose," which completely neglects the distribution of dose within the body. The ICRP does not take dose-rate effects into account in the definition of effective dose, so your point is well taken. However, because most radionuclides used in nuclear medicine have rather short physical half-lives, the issue of dose-rate effects may be less important in nuclear medicine than it is in occupational radiation.

Mattsson: When describing radiation risks to patients, I think we need modifying factors to the effective dose values, which perhaps are 2-3 for a group of pediatric patients and say 0.2 for a group of patients over 70 years. Would you like to comment on that?

Toohey: I agree with you completely. Because the effective dose concept was developed for occupational radiation protection, the tissue weighting factors do not include age-dependent factors. Unfortunately, no set of age-related correction factors to risk estimation has yet been developed and agreed upon by the radiation protection community.

Fisher: When using the effective dose equivalent or effective dose, we must keep in mind that the ICRP developed these concepts for application in occupational radiation protection, such as derivation of secondary limits. The radiation weighting factors are conservatively chosen upper values, not necessarily actual values of relative biological effectiveness for specific endpoints. This system provides a construct of long-term detriment for population groups; it should not be applied to estimate short-term biological effects in individuals, such as patients treated for cancer with high-dose radiopharmaceuticals.

Toohey: Of course; in addition to the radiation weighting factors, the tissue weighting factors also are only for stochastic effects, not deterministic.

Rao: A comment to Dr. Fisher: the α-particle RBE values of 3-5 that you quoted are for deterministic effects, ie.g., cell killing. When you consider stochastic effects (e.g., chromosome aberrations), the RBE values reported for α-particles are as high as 80. Therefore using a radiation weighting factor of 20 for α-particles is not unreasonable when our interest is risk assessment.

Akabani: We have opened a Pandora's box. It is clear that the risk associated with a nuclear medicine procedure requires taking into consideration dose rate, age, and organ biokinetics, and must be based on radiation weighting factors for the specific-age population. The risk estimate must also

consider the latency period for a specific illness to occur in a specific-age population.

Eckerman: Regarding age-dependent weighting factors, it appears that it would be much better to go directly from dose to risk in an age-dependent manner rather than attempt to construct and implement such considerations in the age-dependent scheme.

Toohey: All the comments are quite correct; effective dose does not meet all of our needs for a single parameter with which to perform risk-benefit evaluations in nuclear medicine; however, we still feel it is a much better parameter to use for this purpose than is whole-body dose, which we feel is essentially meaningless for any radiopharmaceutical that is not uniformly distributed in the body.