FOETAL DOSE CONVERSION COEFFICIENTS FOR ICRP-COMPLIANT PREGNANT MODELS FROM IDEALISED PROTON EXPOSURES

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Protection of pregnant women and their foetus against external proton irradiations poses a unique challenge. Assessment of foetal dose due to external protons in galactic cosmic rays and as secondaries generated in aircraft walls is especially important during high-altitude flights. This paper reports a set of fluence to absorbed dose conversion coefficients for the foetus and its brain for external monoenergetic proton beams of six standard configurations (the antero-posterior, the postero-anterior, the right lateral, the left lateral, the rotational and the isotropic). The pregnant female anatomical definitions at each of the three gestational periods (3, 6 and 9 months) are based on newly developed RPI-P series of models whose organ masses were matched within 1% with the International Commission on Radiological Protection reference values. Proton interactions and the transport of secondary particles were carefully simulated using the Monte Carlo N-Particle eXtended code (MCNPX) and the phantoms consisting of several million voxels at 3 mm resolution. When choosing the physics models in the MCNPX, it was found that the advanced Cascade-Exciton intranuclear cascade model showed a maximum of 9% foetal dose increase compared with the default model combination at intermediate energies below 5 GeV. Foetal dose results from this study are tabulated and compared with previously published data that were based on simplified anatomy. The comparison showed a strong dependence upon the source geometry, energy and gestation period: the dose differences are typically less than 20% for all sources except ISO where systematically 40–80% of higher doses were observed. Below 200 MeV, a larger discrepancy in dose was found due to the Bragg peak shift caused by different anatomy. The tabulated foetal doses represent the latest and most detailed study to date offering a useful set of data to improve radiation protection dosimetry against external protons.

INTRODUCTION

Protecting a developing foetus and the mother against ionising radiation is of particular importance due to high foetal radiosensitivity⁽¹⁾. Pregnant air travelers and crew members are exposed to galactic cosmic rays, of which swift protons comprise approximately 90%^(2–5). Proton irradiation can also occur in high-energy accelerators used in nuclear physics research where a pregnant female might be present. The high linear energy transfer of the protons makes radiation protection dosimetry for the foetus particularly important^(6,7).

The assessment of organ doses, in general, is non-trivial due to both the complex anatomy of the human body and the radiation physics involved in particle propagation through organs and tissues. Increasingly, researchers have chosen the Monte Carlo radiation transport approach applied to virtual human models, which are realistic and computationally affordable. Stabin *et al.*⁽⁸⁾ designed the first series of stylised models of a pregnant female at the end of each trimester. Chen⁽⁹⁾ further extended the stylised

pregnant female models into four pregnancy periods: 8 weeks, 3, 6 and 9 months. Tabulations from Chen^(10,11) are the only published data on foetal doses due to external proton exposures.

In order to improve the anatomical realism of the pregnant female models, Shi and Xu⁽¹²⁾ designed a voxel-based partial-body model using CT images. This 7.5-month pregnant female patient model had poor resolution. To address the need for realistic whole-body models at various gestational periods, Xu *et al.*⁽¹³⁾ developed a set of models—the RPI-P series. This method employed a novel Boundary REpresentation (BREP), based on polygonal meshes and non-uniform rational b-splines. The BREP approach facilitates the surface deformation and adjustment of organ masses to match the reference values. Other pregnant models include voxel and hybrid phantoms^(14,15).

Currently, the RPI-P series is used for a number of internal and external dosimetry studies. This paper presents a set of fluence to absorbed dose conversion coefficients calculated for these models. Dose conversion coefficients are essential for shielding design, assessment of radiation risk to individuals (a radiation worker, an astronaut, an air crew

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member, etc.). In this study, an external whole body irradiation with monoenergetic broad proton beams of six standard configurations and 12 source energies from 100 MeV to 100 GeV were simulated using the Monte Carlo N-Particle eXtended code (MCNPX) and continuous-energy nuclear data libraries⁽¹⁶⁾.

MATERIALS AND METHODS

RPI-P geometry and compositions

Recently RPI-P3, -P6 and -P9 computational phantoms have been developed to represent individuals at 3, 6 and 9 months of pregnancy⁽¹³⁾. The use of boundary organ surface representation (BREP) instead of voxels facilitated their size and shape adjustment. The organ masses were adjusted to match the reference data on average pregnant females^(17,9). Table 1 in Taranenko and Xu⁽¹⁸⁾ summarises the organ masses in detail. An excellent agreement with reference masses of less than 1% for all 35 organs were achieved, except the eye lens which has a 4% discrepancy with the International Commission on Radiological Protection (ICRP) value due to the small organ size.

In this study, the version 2 of the original RPI-P series was used with the following two minor modifications:

- (1) The volume of the urinary bladder contents was reduced in the RPI-P3, -P6 and -P9 models in accordance with Stabin *et al.*⁽⁸⁾. The masses became 128, 107 and 42.3 g, respectively, instead of a fixed 130 g used previously. This change reflects the smaller bladder that is generally found at later stages of pregnancy.
- (2) The transverse colon was shifted slightly upwards, covering the small intestine and the uterus from above. Such an arrangement does not affect the foetal shielding, but is more consistent with anatomical changes due to enlarged uterus⁽⁸⁾.

Since particle tracking in the voxel domain is still faster than using meshes, the anatomical models at a 3 mm resolution were voxelised after the anatomical changes had been made. The voxelisation algorithm has a feature to reassign a small percentage of voxels between the adjacent organs in order to correct for the discretisation error and yield a less than 1% match with the reference volumes. The reason for the use of the 3 mm voxels instead of finer size was the limitation in the total number of voxels in MCNPX version 2.5.0. The three models, RPI-P3, -P6 and -P9, yielded 10, 13 and 15 million of voxels, respectively, of which 2.5–3 million represent 35 different tissues and organs. The MCNPX is a multi-particle, all-energy (eV–TeV) Monte Carlo general purpose transport code from Los Alamos

Table 1. Fluence-to-absorbed dose conversion coefficients to the whole foetus in the RPI-P3, -P6 and -P9 models exposed to proton beams of various geometries and energies.

E_0 (GeV)	Absorbed dose per unit fluence (pGy cm ²)				
	AP	PA	LAT	ROT	ISO
RPI-P3 model					
0.1	814	2.20	1.62	166	152
0.15	1370	1240	1185	1130	762
0.2	949	1080	1130	1110	1000
0.3	705	739	731.5	744	744
0.5	594	621	611.5	618	612
1	611	651	628.5	637	632
2	649	704	682	675	694
5	808	907	905.5	887	937
10	1020	1170	1165	1140	1190
20	1250	1460	1510	1480	1550
50	1500	1880	1930	1880	2040
100	1750	2210	2350	2230	2530
RPI-P6 model					
0.1	925	1.60	157	369	376
0.15	1140	465	1240	833	720
0.2	957	957	1050	1030	936
0.3	696	762	723	726	733
0.5	584	619	606	604	601
1	595	650	627	627	623
2	631	709	674	672	675
5	796	983	875	886	921
10	1010	1300	1120	1130	1190
20	1240	1700	1425	1470	1550
50	1520	2310	1810	1860	2040
100	1780	2840	2155	2280	2550
RPI-P9 model					
0.1	744	1.45	397	383	357
0.15	1050	270	1140	836	731
0.2	1020	719	1040	984	889
0.3	698	766	722	727	736
0.5	582	616	609	606	599
1	596	648	629	625	621
2	637	717	677	678	674
5	814	1020	872	901	919
10	1030	1340	1115	1160	1200
20	1290	1780	1415	1490	1560
50	1610	2440	1780	1920	2080
100	1920	3100	2130	2360	2570

National Laboratory⁽¹⁶⁾. Its latest improvements enabled effective voxel geometry definition and dose scoring. The voxel geometry in MCNPX was set up using repeated structures^(18,19).

A total of 35 organs and the corresponding 20 tissue materials with unique elemental compositions and densities were specified in the anatomical models using data from the ICRP⁽¹⁷⁾ and International Commission on Radiation Units and Measurements⁽²⁰⁾ and were previously summarised in Table 2 of Taranenko and Xu⁽¹⁸⁾. The 13 elements were mapped to their corresponding isotopes.

Table 2. Fluence-to-absorbed dose conversion coefficients to the foetal brain in the RPI-P3, -P6 and -P9 models exposed to proton beams of various geometries and energies.

E_0 (GeV)	Absorbed dose per unit fluence (pGy cm ²)				
	AP	PA	LAT	ROT	ISO
RPI-P3 model					
0.1	2.91	2.54	1.52	2.20	2.94
0.15	1500	1680	89.5	1320	827
0.2	1000	1000	1200	1140	994
0.3	706	711	733.5	751	739
0.5	589	601	602	621	614
1	634	635	631	644	625
2	675	664	670	664	693
5	847	857	917	842	936
10	1090	1130	1180	1140	1210
20	1350	1360	1575	1460	1590
50	1690	1680	1990	1820	2070
100	1950	2020	2510	2230	2550
RPI-P6 model					
0.1	2.39	2.04	1.66	2.12	24.4
0.15	1230	1320	1172	802	553
0.2	1070	1080	1085	1130	1050
0.3	723	737	741.5	743	741
0.5	605	624	624	636	609
1	630	651	656	658	646
2	699	707	715	720	702
5	898	915	949	943	987
10	1160	1200	1220	1220	1280
20	1470	1540	1570	1610	1700
50	1870	2020	2020	2000	2230
100	2250	2370	2415	2480	2760
RPI-P9 model					
0.1	2.00	2.27	1.84	4.02	51.0
0.15	279	1160	829	824	593
0.2	1370	1090	1150	1160	992
0.3	738	735	745	736	753
0.5	606	617	627	626	613
1	643	649	661	655	651
2	705	703	723	715	716
5	959	925	964	958	985
10	1240	1200	1245	1220	1290
20	1640	1540	1625	1570	1710
50	2180	2000	2110	2040	2300
100	2690	2380	2605	2490	2860

The mapping was based on the availability of cross-section data. Preference was given to a natural isotope mixture; otherwise, a stable most abundant isotope was substituted. The new cross-sections at room temperature with finer energy resolution, photon and charged particle yields and higher maximum energy of projectile (up to 150 MeV) were adopted.

Present release of the RPI-P series includes three foetal organs: the brain, the skeleton and the remaining soft tissue. Whereas the skeleton distributed rather uniformly throughout the foetus and

therefore its dosimetric dependencies on irradiation geometry and source energy are expected to follow those for the whole foetus, the brain located asymmetrically at the distal end of the body is centred in the mother's pelvis. Given those anatomical differences only the dose to the foetal brain is reported in addition to its whole body dose. The dose to the foetal skeleton and the soft tissue as well as to the maternal organ can be requested from the authors.

Sampling proton source

Six idealised irradiation geometries were considered: the antero-posterior (AP), the postero-anterior (PA), the right lateral (RLAT), the left lateral (LLAT), the rotational (ROT) and the isotropic (ISO)⁽²¹⁾. The first four unidirectional fields plus the ISO field were sampled using the standard MCNPX general purpose source. The ROT source was modelled by a user-defined sampling algorithm⁽¹⁸⁾. The primary monoenergetic proton beams have 12 different energies from 100 MeV to 100 GeV. Five million primary protons were assigned for most Monte Carlo runs, which yielded 1–3% coefficient of variance for the foetal dose. For very low or high energies and the tiny 3-month foetal brain, the total number of histories was increased up to 400 million in order to keep the statistical uncertainty below 5–7%.

Physics modelling in MCNPX

To accurately simulate various interactions and energy deposition channels all 35 secondary particle types were considered in the transport, including neutrons, deuterons, tritons, ³He, alphas, photons, electrons, mesons and other leptons. MCNPX combines cross-sectional data and nuclear physics models when cross-sections are not available (mix-and-match feature).

Only the following six nuclides, including those with major abundances, were found to have cross-sections available in the LANL library LA150H: ¹H, ¹²C, ¹⁴N, ¹⁶O, ³¹P and ⁴⁰Ca. The physics models were used via mix-and-match algorithm for protons above 150 MeV and for missing cross-sections below 150 MeV. Models, at all energies, transported the other heavier charged particles. Vavilov charged particles energy straggling control was employed.

In the intermediate energy range, above the nuclear structure region from 150 MeV to a few GeV, the most common modelling methods include intranuclear cascade (INC), pre-equilibrium and evaporation models. The default combination of physics models, Bertini/ISABEL/Dresner, was used in the simulations⁽²²⁾. The following models: elastic scattering for both neutrons and protons, the use of pre-equilibrium models after intranuclear cascade, the use of the Bertini model for nucleons and pions and the

ISABEL model for other particle types were also employed. For energies above a few GeV (the natural limitation of INC physics), MCNPX handles high-energy interactions using the quantum approach inherited from an early version 87 of the Fluka code⁽²³⁾.

The transport of the secondary neutrons is important in dosimetry of high-energy protons. Cross-sections based on the Evaluated Nuclear Data File format (ENDF) evaluations, VI.8 and VI.6 are available up to 150 MeV⁽¹⁸⁾. The $S(\alpha, \beta)$ thermal scattering treatment for hydrogen in light water at 294 K was based on the library SAB2002 (ENDF/B-VI.3 evaluation 1999).

The detailed model for photon interactions for energies below 100 MeV, including coherent scattering, fluorescence after photoelectric absorption, Compton scattering and pair production were used. For energies above 100 MeV, simple photon physics was used without coherent scattering and fluorescence. The latest MCPLIB04 cross-sectional library for photoatomic interactions based on EPDL 97 evaluation was employed. The library spans from 1 keV to 100 GeV.

For the electron transport, the standard library EL03 was used. This library provides data up to 1 GeV. In MCNPX, the data at 1 GeV is used by default for the electron transport at higher energies. The electron energy cut-off was set to be 70 keV, which corresponds to approximately 0.3 mm electron range in the lung—one-tenth of the voxel dimension. The ITS indexing algorithm was used.

Among the standard MCNPX photonuclear cross-sections (library LA150U by the Nuclear Physics Group, Los Alamos National Laboratory), only three nuclides were available: ^{12}C , ^{16}O and ^{40}Ca . For other nuclides, the photonuclear physics models were employed by the mix-and-match MCNPX algorithm.

Effect of an alternative physics model, Cascade-Exciton Model

To check the sensitivity of the results on physics employed, the doses calculated with the default Bertini/ISABEL/Dresner physics models against the alternative Cascade-Exciton Model, version 2000 (CEM2k) at the intermediate energies of 100 MeV–5 GeV were compared. CEM2k allows protons, neutrons and pions to initiate nuclear reactions on nuclei with $Z > 5$ and $A > 11$. The interactions with light nuclei are passed to standard Bertini/ISABEL models that use the Fermi-breakup model in this regime. CEM2k consists of an intranuclear cascade model followed by a pre-equilibrium and evaporation models. After evaporation, gamma rays are generated via de-excitation of the residuals.

The comparison between the default physics models and CEM2k was performed for the foetal

dose in the RPI-P9 model and the AP beam. The results showed a systematic dose increase of up to 9% at 2 GeV for the whole foetus and its brain (at 1–2% coefficient of variance for compared doses). It is beyond the scope of this study to analyse the applicability of high-energy nuclear models available in MCNPX. To report doses calculated, it was decided to use the standard set of models, recognising that a 9% dose increase observed in CEM2k model reflects the uncertainty of physics modelling.

Scoring

The scoring of energy deposition in about 30 organs was accomplished via the collision heating tally (+F6), which is a track-length estimate. Proton and neutron energy depositions are determined using heating numbers—energy deposition estimates per unit track length. Ionisation contribution, dE/dx , was also taken into account for all charged particles assuming a uniform deposition along the track length. For missing cross-sections, in addition to ionisation, other energy depositions at the time of the nuclear interaction were calculated. The energy of the secondary particles excluded from the transport was deposited locally. In MCNPX, protons and neutrons undergoing elastic scattering with light nuclei (^1H , ^2H , ^3H , ^3He and ^4He) can create ions (protons, deuterons, tritons, ^3He and alpha) that are stored for subsequent transport. This light ion recoil generation and subsequent transport was set in all simulations.

The importance of secondary particle transport

The absorbed dose consists of contributions from the primary protons, secondary protons, neutrons, electrons and other transported heavy charged particles generated in the body. Figure 1 illustrates the typical production of secondary particles in the entire body of the RPI-P9 model for the AP beam, where all generations (secondary, tertiary, etc.) of particles production were taken into account. As expected, a maximum number of secondaries—about 20 particles per source proton—are generated at the highest energy of 100 GeV. Secondary particles consist primarily of electrons and photons above 1 GeV and protons at lower energies. The largest fraction of photons is created via electron bremsstrahlung, whereas the majority of electrons are produced in the direct knock-on ionisation. As the greater electron multiplication is obvious at higher energies, it is the pair production that initially sets the electrons in motion with high energies (particle decay being a second priority channel).

Pion transport is important ≥ 1 GeV. Test runs without pion transport (but with all other secondary particles) show an almost 2-fold dose

Figure 1. Dominant generation of secondary electrons, photons and protons. The number of secondary particles per source proton, N , as a function of initial proton energy is shown for the RPI-P9 model and the AP beam. Kaons, which give negligible number of tracks, were excluded from the graph.

underestimation at 100 GeV. A mechanism describing the physical processes that happen at this energy is as follows. About 80% and 40% of source photons are involved in nuclear interactions that result in production of pions, π^+ and π^0 , respectively. The vast majority of charged pions escape the modelling geometry and about 15% participate in nuclear interactions. However, π^0 decays via electromagnetic mode (99% probability) into two high-energy photons of 1.6 GeV for a 100 GeV proton source. This is a major channel of photon production of highest energy. Consequently, it gives rise to the pair production where the high-energy electrons are generated and later multiplied via the knock-on described previously.

Figure 2 depicts the total absorbed dose to the foetus along with partial charged particle contributions. One can see the dominant contribution of protons at all energies. It is important to bear in mind that the proportion of the secondary protons increases with energy, reaching a maximum number of 1.6 secondary protons per source proton (Figure 1). The direct charged pion contribution in the dose reaches a maximum of almost 50% with that of protons at 100 GeV. Pions, however, mediate a dose deposition even at lower energies and must be explicitly included in the particle transport.

RESULTS AND DISCUSSION

The statistical uncertainty of the foetal dose estimates was kept below 5–7% for the foetal brain and 3% for the whole foetus. All results were normalised per unit source fluence.

Figure 2. Prevailing contribution of protons to the absorbed organ dose. The absorbed dose to the foetus (normalised per unit fluence) is shown as a function of source proton energy for the RPI-P9 model and the AP beam. Partial contributions of charged particles are also shown. Kaons and muons contribute a negligible fraction of dose.

Foetal doses for RLAT and LLAT irradiation geometries (LAT notation) due to negligible difference in foetal doses for majority of energies were averaged, at all beam geometries and for all three phantoms. The dose to the whole foetus differs by only few percent between the two lateral geometries for source energies above 200 MeV. At 100 and 150 MeV, however, the difference reaches 8% in all three models. For the foetal brain, the doses agree within statistical uncertainty for all beam directions and energies, except at 150 MeV, where the RLAT beam showed a factor of 2.7 and 1.4 increase in the RPI-P3 and -P6 models, respectively. At low proton energies, a slight change in the attenuation mass can have a significant impact on the Bragg peak location and the amount of energy deposited inside the foetus. Therefore, the lack of perfect symmetry for the foetus location causes the difference in calculated dose from the lateral beams.

Results for the whole foetus, i.e. including the brain, the skeleton and the soft tissue, are presented in Table 1.

Figure 3 shows the dependence of the foetal total dose (per unit source fluence) upon irradiation geometry as a function of initial proton energy. The dose has a local maximum in the 150–200 MeV interval, due to the Bragg peak located directly within the foetus. It increases monotonically above 400 MeV for all geometries and models. Below 200 MeV, the foetal total dose is strongly dependent upon the source geometry—up to a factor of about 600 at 100 MeV. At higher energies, this effect gradually diminishes and the difference is reduced to

Figure 3. Energy dependence of dose conversion coefficients for the whole foetus. Monte Carlo results for five source configurations (AP, PA, LAT, ROT and ISO) are shown in comparison to the RPI-P3, -P6 and -P9 models (A, B and C, respectively).

10–60%. For all three models, the AP beam yields the highest foetal dose at 100 MeV, whereas PA dominates above 200 MeV (except P3 where ISO doses are slightly higher). The lowest doses below 200 MeV are received in LAT beam in the P3 model and in PA irradiation in P6 and P9.

Table 2 shows the results for the *foetal brain*. Similar to the foetal dose results, the dependence on the irradiation geometry is noticeable below 200 MeV—up to a factor of 30 at 100 MeV in P3. Above 2–5 GeV, the maximum brain dose is observed for the ISO beam in all models, although the difference between the source beams is less than 20–30%. Energy dependence of the foetal brain dose is similar to those of the total foetus.

Chen⁽¹⁰⁾ published the only available data set known to the authors on the proton foetal doses for six standard irradiation geometries. The work was based on the ORNL mathematical models of simplified anatomy. Additional tabulations were provided for top-down (TOP) beams by Chen⁽¹¹⁾. The authors plan to discuss simulations for this type of irradiation geometry specific for the high-altitude

flight in a separate paper covering other types of source particles as well.

For the six standard geometries and for almost all energies above 200 MeV, Chen found a maximum foetal dose in the PA beam, although the other beams yielded comparable doses. Only in the ISO field the foetal dose was found to be distinguishably lower. The foetal brain dose showed similar energy dependency.

Figure 4 compares the results for the total foetus with those published by Chen⁽¹⁰⁾. Above 200 MeV for both whole foetus and its brain, the discrepancy in dose is less than about 20% for all beams except ISO. The latter shows systematic 40–80% dose increase in RPI-P models. The likely reason for that is the more extended spatial allocation of the phantom body that intercepts more particles, particularly in the ISO field compared with the compact mathematical phantom geometry.

Below 200 MeV, the comparison for all geometries shows a larger discrepancy, reaching a lowest value of 0.002 and a maximum of 36 at 100 and 150 MeV in a few cases. This could be attributed to the

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Figure 4. Ratio of RPI-P foetal doses to those published by Chen (2006) for the whole foetus (A, C and E for RPI-P3, -P6 and -P9, respectively) and its brain (B, D and F for RPI-P3, -P6 and -P9, respectively) as a function of source proton energy. Five standard irradiation geometries (AP, PA, LAT, ROT and ISO) and 3, 6 and 9 months models are shown.

sensitivity of the Bragg peak location upon the foetus shielded by the mother's body. In the ISO field of low energies, those anatomical differences of the whole phantom are revealed to a greater extent compared with other irradiation geometries.

CONCLUSION

The absorbed dose conversion coefficients for the whole foetus and its brain for six idealised external proton beams (AP, PA, RLAT, LLAT, ROT and ISO) at energies 0.1–100 GeV were calculated, using the RPI-P series of voxel phantoms at the 3 mm resolution. Propagation of protons along with important secondary particles was carefully simulated using the MCNPX Monte Carlo code. When choosing the hadron physics simulator in MCNPX, it was found that the advanced CEM2k intranuclear cascade model yields a maximum of 9% foetal dose increase than the default models at intermediate energies below 5 GeV.

The results for the whole foetus and its brain are tabulated and compared with the only published

data of Chen^(10,11). Depending on the irradiation geometry, energy and gestation periods, agreements within 20% or less were found for both the whole foetus and its brain above 200 MeV. However, the ISO exposure revealed a systematic dose increase of 40–80%. For energies below 200 MeV, the discrepancy is primarily attributable to differences in the anatomical models and dose ratio reaching extreme values of 0.002 and 36 due to the difference in Bragg peak location. An improved anatomical realism of RPI-P models justifies the deviation from the previous dose estimates.

The RPI-P models are currently used for various internal and external dosimetry studies in health and medical physics^(18,24,25). Since the RPI-P phantoms are realistic and adjusted to match the ICRP references, and the Monte Carlo physics models were carefully investigated, the tabulated data in this study and elsewhere offer consistent data to improve the radiation dosimetry of a pregnant female. Particle transport at energies 20–200 MeV—where cross-sections end and physical models take precedence and where discontinuity in dose to

superficial organs was found—is a subject for further investigation.

Though the present RPI-P phantoms include only three foetal organs, the method of 3D modelling used in their construction allows for embedding new organs.

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