Ref. Ares(2020)65489 - 07/01/2020

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 662287.

EJP-CONCERT

European Joint Programme for the Integration of Radiation Protection Research

H2020 – 662287

D9.119 - Report summarising the computational developments needed to realise full online dosimetry using simulation of voxel phantoms in the workplace

Lead Authors: Jon Eakins, Olivier Van Hoey and Rick Tanner
With contributions from: Mahmoud Abdelrahman, Eftychia Kouroukla and Pasquale Lombardo

Reviewer(s): Filip Vanhavere and CONCERT coordination team

Work package / Task	**WP 9** **ST9.6 (PODIUM)**	**SST9.6.0.1**
Deliverable nature:	**Report**	
Dissemination level: (Confidentiality)	**PU**	
Contractual delivery date:	**2019-12-31 (M55)**	
Actual delivery date:	**2020-01-07 (M56)**	
Version:	**1**	
Total number of pages:	**13**	
Keywords:	**Neutron dosimetry, computational dosimetry**	
Approved by the coordinator:	**M56**	
Submitted to EC by the coordinator:	**M56**	

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Abstract

It was acknowledged at the outset of this project that real time online dosimetry with full Monte Carlo modelling in anthropomorphic phantoms would be too severe a challenge for workplaces where neutrons contribute a significant fraction of the total effective dose. The reasons for this are complex, with the scale of neutron workplaces, the inherently mixed-radiation nature of the fields and the strong scattering experienced by neutrons in the workplace being factors. But there is a fundamental issue with the application of energy dependent radiation weighting factor in the workplace for voxelized phantoms which forces the use of a two-step Monte Carlo process: initial calculation of the energy and direction distribution of the fluence at a point, and then the application of precalculated energy and angle dependent fluence to effective dose conversion coefficients. This is because the radiation weighting factor applies to the energy of the neutron as it enters the body, rather than the energy of the neutron that is depositing the energy: neutrons deposit energy in several interactions but the Monte Carlo code cannot apply a weighting for the absorbed dose deposited based on the energy of the neutron as it entered the body.

CONTENT

1. Introduction

The ultimate aspiration for online dosimetry is the real time transport of radiation from the source(s) to deposition of the energy in an organ or tissue in a realistic representation of a person. The radiation may travel directly from the source(s) to the body, or undergo significant scatter on its way to the body, and the radiation source could emit various particles via a variety of reaction mechanisms. Some of the particles emitted may be short range, but they can still generate longer ranged secondaries which would need to be considered.

For many workplaces the radiation of interest for whole body exposures is limited to photons and betas, but if there are fissile materials present, neutrons will become a component of the field, and where there are high energy gamma rays or alpha particles, (γ,n) and (α,n) reactions can generate neutrons to which people are exposed. Accelerator and space environments include neutron components via other interactions and may include significant dose components from other particles. So, mixed-fields containing neutrons will need to be addressed for widespread application of online dosimetry. In some fields the neutron dose rate dominates so the neutron component can be of primary importance [Schuhmacher et al., 2006]

PODIUM has sought specifically to address the issue of neutron rich workplaces. But workplaces with a significant neutron field will also include a significant component of dose from photons: the source is likely to emit primary photons, but neutrons also generate secondary photons via (n,γ) reactions. The ultimate solution should hence include calculation of the neutron and photon doses simultaneously, but in PODIUM we looked mainly at the neutron part in these mixed fields.

Monte Carlo calculations for neutron transport pre-date photon Monte Carlo, but the calculations are known to be relatively slow and computationally demanding when compared to those for photons. This is true for several reasons, including:

- Neutrons are strongly scattered in the environment, which means that each particle history can be complex;
- Once thermalized the neutrons effectively diffuse “slowly” through a medium undergoing many computationally expensive elastic scattering interactions;
- The cross-section files are necessarily very large because of the wide energy range, number of different reaction channels and the strong variation with energy, especially where there are resonances;
- The large cross-section differences that are observed for different isotopes of the same element;
- Neutron workplaces can be very large in scale and the neutrons may have suffered many scattering events and a lot of attenuation before they get to locations where people may be.

Taken together, these effects make the computational problems for online dosimetry in mixed neutron-gamma fields more complex, both in terms of computation times and memory requirements. For these reasons, and because of difficulties with the definitions of the dose quantities (see Section 2), PODIUM has settled on a “look-up table” approach for mixed fields containing neutrons. This deliverable looks at what would need to be improved to get around the look-up table approach.

2. Issues with effective dose and $H_p(10)$

In principle, if an anthropomorphic phantom can be translated through the Monte Carlo geometry in real time, and perhaps flexed into realistic postures, then the actual effective dose that is being received by an individual could be calculated as it happens. In practice, this is difficult for all radiation types but for mixed neutron/photon fields there are added complexities associated with the definitions of the dose quantities that make it hard to achieve currently.

There is one difficulty in terms of the definition of effective dose that applies to all radiation types: it is defined in specific anthropomorphic phantoms with sex-averaging. Specifically, ICRP [ICRP, 2007] defines effective dose as an average of values calculated in the reference male and female adult phantoms [ICRP, 2009]: this definition has been used in the calculation of the reference effective dose conversion coefficients [ICRP, 2010]. However, the reference values only consider monoenergetic exposures to single radiation types in a vacuum for well-defined geometries. Calculating effective dose for these simple fields and geometries is much less complex than doing it in a simulated workplace.For pure low linear energy transfer (L) fields, composed of photons and electrons, the scoring of the absorbed dose in a phantom is all that is required to generate conversion coefficients for any of the relevant dose quantities. This is because the radiation weighting factor, w_R, and the quality factor, $Q(L)$, are both 1 for all energies. Consequently, both effective dose and personal dose equivalent can be calculated for workplace scenarios where the penetrating radiation is dominated by photons, though whether or not the latter quantity is truly desirable may be field-dependent because $H_p(10)$ can be a poor estimator of risk for individuals not exposed from the front. For neutrons, however, both the w_R and $Q(L)$ are energy dependent, with the absorbed dose being weighted either by a w_R value (for effective dose) determined by the energy of the neutron that entered the phantom, or by a $Q(L)$ (for dose equivalent) that is dependent on the energy of the charged particles released at the point of interaction.

The energy-dependence of w_R causes problems for the Monte Carlo calculation of effective dose in non-monoenergetic fields (i.e. in all realistic workplace fields) because the energy of the neutron that entered the body may be different from the energy of the neutron that is interacting at a given point-of-test (e.g. in an organ or tissue). Additionally, any secondary photons that deposit dose in the body should also have the w_R of the originally incident neutron applied to them. This causes difficulties, since for a particle tallied by the Monte Carlo code there is no simple method of 'retrodicting' the energy that the neutron had when it was originally incident on the body, such that the correct w_R may be identified and applied. This is a seemingly intractable problem for voxel phantoms in complex geometries that prevents effective dose from being calculated in distributed energy fields. This, as well as computation time issues, is the reason why PODIUM has favoured a look-up table approach for neutrons. All options for real time voxel phantom calculations are hence more complex because of the need for a two-step process, whereby the fluence of the field is resolved in direction and energy before effective dose is calculated by applying precalculated energy and angle dependent fluence to effective dose conversion coefficients.

Calculation of $H_p(10)$ for neutrons is simpler, because there are approximation methods to generate dose equivalent [Siebert and Schuhmacher, 1995] and some Monte Carlo codes have inbuilt $Q(L)$ modelling [Pelowitz, 2013]. In a mixed field the total $H_p(10)$ can be scored accurately within the phantom in a full neutron-gamma Monte Carlo calculation, but the separate neutron and photon contributions will be incorrect because whilst (n,γ) reactions within the phantom should contribute to neutron $H_p(10)$ they will actually be scored as a part of photon $H_p(10)$. However, this conceptual difference would not matter for an operational online dosimetry system where only the total $H_p(10)$ would be of importance,

because the underestimate of the neutron $H_p(10)$ would be exactly balanced by the overestimate of photon $H_p(10)$. Nevertheless, and as mentioned previously, $H_p(10)$ is a poor estimator of risk in some fields, such as when exposures are predominantly from behind (PA) or the sides (LLAT and RLAT), so its relative ease of calculation compared to E would be outweighed by its inaccuracy of risk estimation. Calculation of $H_p(10)$ may therefore not be viewed as adequate for online dosimetry, though it is noted that similar problems also arise for physical dosimetry in such cases if the dosemeter is worn on the front of the individual. The ICRP and ICRU might adjust the definitions of the dose quantities in the future in a way that makes online dosimetry easier or more bespoke to a given individual. ICRP have already published a consultation on environmental dosimetry that does not restrict the calculation of effective dose to the reference phantoms, though they maintain the sex averaging. For online dosimetry there would therefore be the potential to choose a phantom that provided a better description of the exposed person than is currently allowed by ICRP [ICRP, 2007], such as through the use of larger or smaller reference individuals. However, for an online dosimetry system to be acceptable to the ICRP it may still need to produce sex-averaged results, unless ICRP modified their definition of effective dose. Alternatively, it may be considered that the uncertainties associated with using a male or female reference phantom are small compared to the uncertainties associated with the use of personal dosemeters, so sex-averaging is of secondary importance. This applies as much to mixed photon-electron fields.

ICRP currently have a consultation underway on the use of mesh-type reference computational phantoms (MRCPs) as a potential alternative to voxel phantoms. These are more flexible in terms of posture and size than voxel phantoms and might offer faster computation. However, in the draft document ICRP do not recommend that these should replace the reference voxel phantoms. It is intended that reference MCRPs will be made available with the published report for use with MCNP6 [Pelowitz, 2013], PHITS [Sato et al., 2013]and Geant 4 [Allison et al., 2016]. Already MCRPs have been used to generate alternative conversion coefficients for external exposures from photons, electrons, neutrons, protons and helions [Yeom et al., 2019a, Yeom et al., 2019b]. They have been used in WP2 of PODIUM for photons only and do offer the potential for easier and more accurate real time Monte Carlo calculations in the workplace.

Changes to the protection quantity could also potentially involve a return to an effective dose equivalent type of definition, which ICRP have already recommended for astronauts [Dietze et al., 2013]: this could be scored relatively easily by all the main Monte Carlo codes because the energies of the particles at the scoring location would determine the contribution to equivalent dose, not the energy of the neutron as it enters the body. Such a change would make real-time online dosimetry for neutron effective dose equivalent easier to implement as a one-step process.

There are also proposed changes to the operational quantities [Endo, 2015], which could impact on online dosimetry. The current proposal to replace *personal dose equivalent* with a quantity *personal dose* might make the process online dosimetry simpler: *personal dose* is defined using the ICRP reference phantoms, but it is a property of the field at a point. There is some lack of clarity about whether the new quantity would be “receptor present” or “receptor absent”, which does affect the ease with which it could be calculated. But if the quantity is receptor absent, then the field at a point could be scored and energy and direction dependent conversion coefficients based on effective doses could be applied. Real-time calculation of personal dose could therefore be achieved without the difficulties associated with identifying the correct w_R, and yield results that do not possess the inadequacies of $H_p(10)$ for highly oblique exposures. Conversely, if it is receptor present, the reference anthropomorphic phantoms would need to be introduced into the model, rather than a simple slab of ICRU tissue as is the case for personal dose equivalent, which would lead to the same, or if not harder, difficulties as those currently manifest for real-time calculations of effective dose.

3. How much radiation?

It has already been highlighted that for real time Monte Carlo the speed of the calculations is a critical factor; this is especially so for neutrons, which are particularly computationally demanding. The following analysis is intended to provide a handle on the computational resources that would be needed to perform calculation in real time, though obviously there are several caveats to this. Firstly, any observations that can be made are dependent on processor speed and the acceleration methods (e.g. variance reduction techniques) that are available. Secondly, the scale and complexity of the workplace will also be key, because the transport of the neutrons (and photons) to the location of the person might consume a lot of the computing power, even before the dose deposited in the phantom can be computed. Finally, with the person moving within the workplace, any variance reduction would need to be reoptimized as they move, or it would be unable to accelerate the calculations significantly. So, whilst it is useful to estimate what is required to get statistically valid results, and to assess whether it is feasible to do the calculations in real time, such estimates will inevitably be imprecise and strongly dependent on the workplace.

Personal dosemeters often have reporting thresholds around 0.1-0.2 mSv integrated over wear periods of weeks or months, and poor statistical precision even for higher doses. Online dosimetry may aspire to do better, perhaps obtaining a statistically valid result for a single entry to a workplace. Such entries may last several hours, but the focus for online dosimetry systems could be on short entries into high dose rate environments. This therefore sets a benchmark for the current analysis: in general, the dose received by an individual over a shift is most likely all that is required to be recorded with acceptable statistical precision. Of course, statistically robust instantaneous estimates would also be important if the online dosimetry system were to operate with an alarm capability, for example to detect dose-rate 'spikes', but this circumstance is not considered further here.

Neutron fluence to effective dose conversion coefficients range from about 10 pSv cm^2 for thermal and intermediate neutrons to 300 pSv cm^2 for fast neutrons. As a result, it is necessary to have about 10^9 thermal neutrons or $3x10^7$ fast neutrons incident on the individual per square-centimetre to produce a dose of 1 μSv. It follows that for a dose rate of 1 μSv h^{-1} to be received, a fluence rate of about 10^4 cm^{-2} s^{-1} would be required at the location of the individual. However, many more neutrons would have to leave the source to achieve this fluence rate at the location of the person.

Consider simulating such a scenario, and for simplicity assume that the source emits isotropically in vacuum. Assume also that an individual were one meter from this source for only 1 second, before moving away elsewhere. Additionally, assume that the fluence from the source at 1 m is to be determined in the Monte Carlo calculation using a tally with a cross-sectional area of 1 cm^2, orientated perpendicular to a radius of the sphere centred on the source. Finally, assume that the calculation is to be performed on a single CPU core. Then, for the online dosimetry system to be effective, it would have to correctly estimate, within an acceptable degree of precision, the true dose-rate to the individual to within just one second of CPU time. For simplicity, and without loss of generality, let this acceptable degree of precision be ±10 %.

In such a circumstance, only 1 in 125664 particles ($=4\pi\times(100)^2$) that are emitted from the source would on average be scored, giving a fluence of $\sim 7.96\times10^{-6}$ cm^{-2}. Moreover, if only 125664 particles were simulated in the Monte Carlo calculation, the statistical uncertainty on the result would be of the order of 100 %, because it could be expected to follow a Poisson distribution and hence scale broadly with the square-root of the number of particle tracks. To achieve the desired statistical precision of 10 %, 100× as many particles would hence need to be simulated, i.e. $\sim 1.3\times10^7$. To perform real-time dosimetry in this case, the Monte Carlo code would therefore need to simulate this number of particle histories per second. Of course, this analysis is for a highly simplified scenario, and neglects in- and out-scatter as well as the contribution from secondary particles, but the result of $\sim 1.3\times10^7$ s^{-1} illustrates the general scale of the computational demands that would be required.

In the SCK-CEN realistic field (see D9.111) the dose rate at Position C, the effective reference position, was about 10^{-15} Sv per source neutron. This would hence require a fluence of about 10^9 source neutrons to generate a dose of 1 μSv. Using the MCNP model, about $2x10^6$ source particles were started per hour, which in effect equates to a dose rate of about 2 nSv h^{-1} in the Monte Carlo model. This calculation used some basic variance reduction by manually setting cell importances[1].

The inability to get neutrons to the scoring position at the same rate at which they get there in the real workplace is only a problem if such high particle fluences are required for acceptable precision in terms of the relevant dose quantities. In this respect $H^*(10)$ is the easiest quantity to model because there does not need to be any transport within a phantom at the point of interest. In this instance, the statistical uncertainty is < 10% for cpu[2] > 25 s (Figure 1) at Position C, which could be considered acceptable accuracy. To achieve approximately 5% statistical uncertainty requires cpu > 100 s which demonstrates the required acceleration for the SCK-CEN workplace that would be required to do the calculations with acceptable accuracy in real time. Running on three of the laptop's four cores approximately cuts the cpu by a factor of 3 to give real time elapsed.

Much bigger reductions in overall CPU time may be possible if the modelling is performed on a PC-cluster with far more cores, if the calculations can be efficiently distributed across the cores. Such task-distribution may be performed either in parallel, where many cores are dedicated to a single calculation in order to greatly accelerate its completion, or staggered, in which different cores perform calculations for different steps of the tracked-individuals motion. As an example of the latter of these, if due to the individual's motion, a new dose-rate calculation is required every second, and if each dose-rate calculation takes 100 s, then Core 1 could perform the calculation for the individual's position after 1 second, Core 2 could perform the calculation for the individual's position after 2 seconds, and so one. Assuming that the cluster contains >100 cores, there would always be a free core available as required; such a mechanism would not quite calculate doses in real-time, having a 100s time-lag, but this would be sufficiently short in practice.

[1] Where two adjacent cells have different "importances" the particles crossing from one to the other are either killed or split according to the relative importances of the cells, where these importances are expected to increase with proximity to the region of interest. For example, if a particle is travelling towards the region of interest and crosses from a cell with an importance of *n* to a cell with an importance of 2*n*, it would be split into two identical particles, thereby improving the statistical uncertainties in the result. Conversely, particles travelling away from the region of interest would have a 50% chance of being killed, which reduces wasted computation. In both cases, internal adjustments are made by the code to maintain fairness and prevent unduly biasing the result.

[2] Running on a Lenovo ThinkPad with an Intel® Core™ i7-770HQ 2.80 GHz processor with four cores

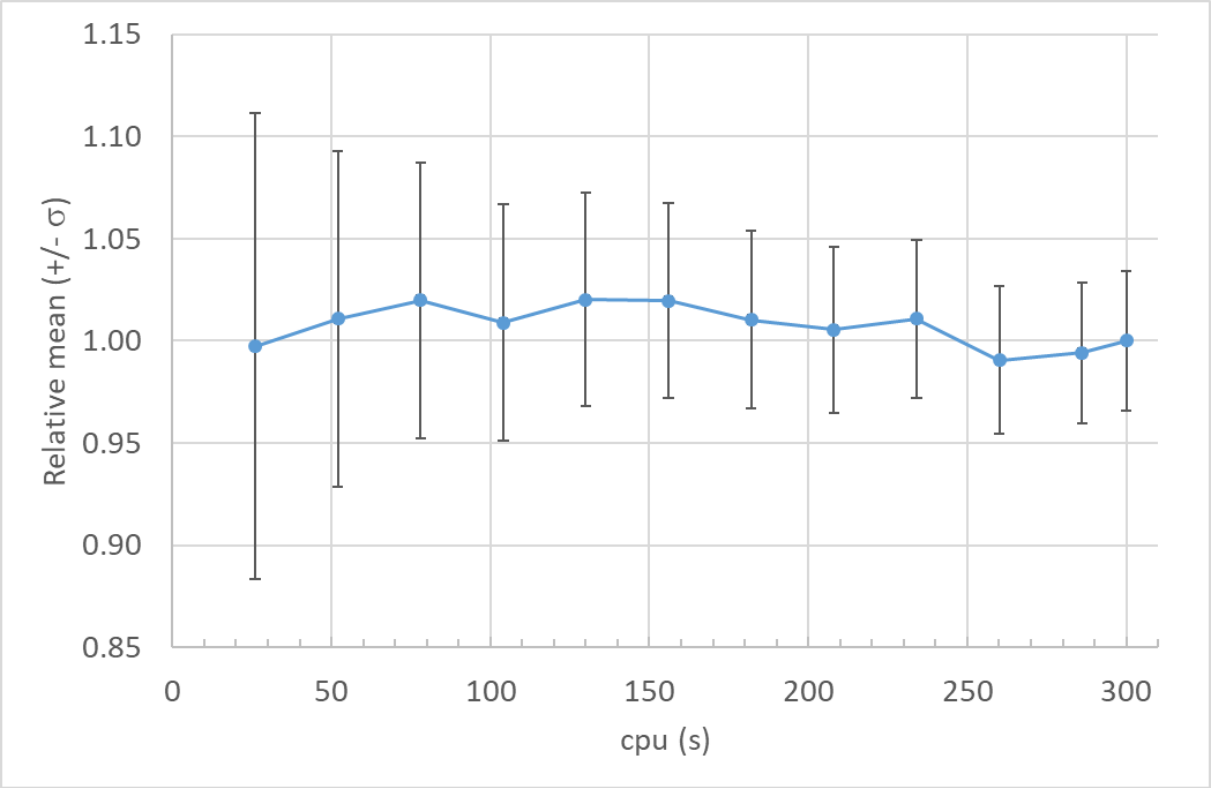

Figure 1. ***Convergence of the mean fluence result for Position C versus cpu elapsed. Uncertainties are the statistical standard deviation of the Monte Carlo result.***

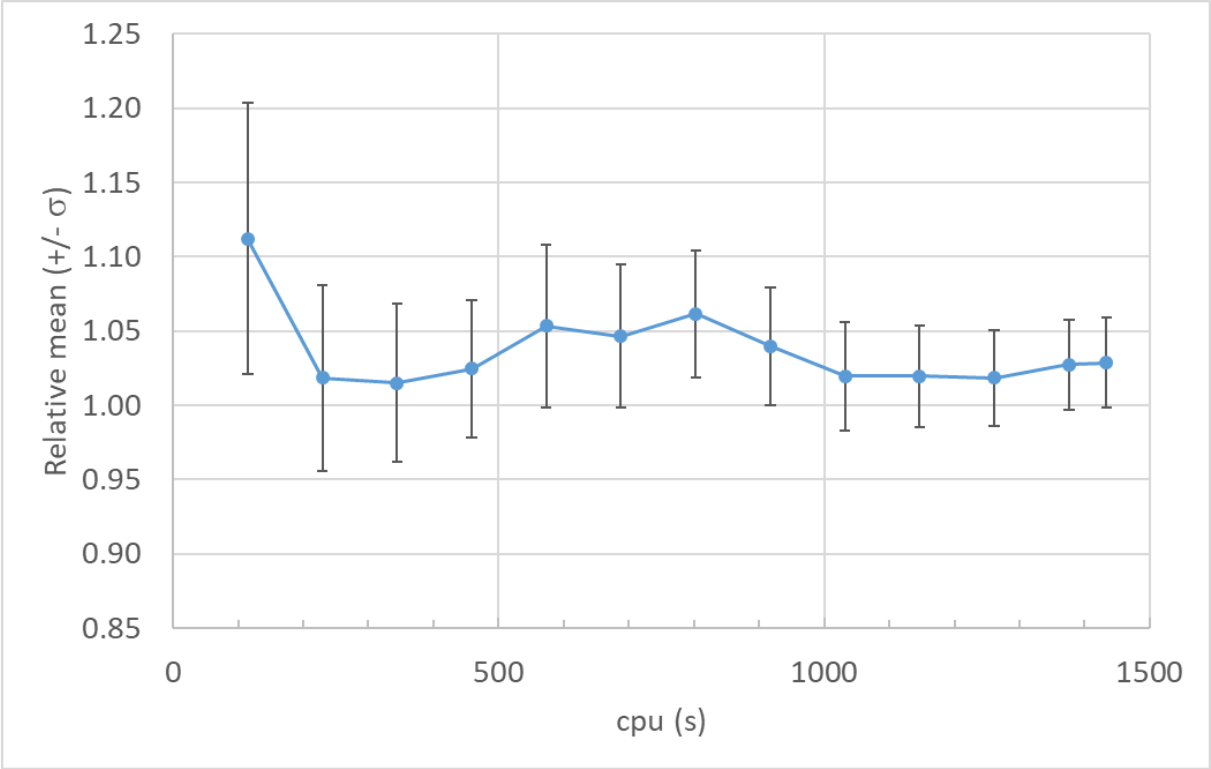

Figure 2. ***Convergence of the mean $H_p(10)$ result for Position C versus cpu elapsed. Uncertainties are the statistical standard deviation of the Monte Carlo result***

If just a voxel phantom were exposed to a plane-parallel, monoenergetic source, a computation time of tens of minutes would be required to obtain acceptable Monte Carlo precision on estimates of effective dose[3]. For realistic geometries, in which the phantom would be inserted into a much larger Monte Carlo model of a workplace, the CPU required to yield organ doses to the same precision would be much higher as a result of an increasing number of particle histories 'missing' the phantom, and hence wasting CPU time. Additionally, codes can take significant times to initialize calculations that feature voxel phantoms, due to the $>10^6$ cells employed in their definitions, which in the case of MCNPX and MCNP6 is about 10 s[4]. This would be a fundamental limitation if a paradigm were envisaged in which a voxel phantom were to be moved within the model of the room geometry in a way that matched the motion of the tracked individual, leading to an unavoidable additional delay in performing that calculation in genuinely real-time.

The statistical precision required for a specific location and orientation may not be so great, because the combined results for a person moving through a geometry will have better statistical precision than the results for each calculation. This needs to be investigated for individuals tracked through a geometry, but the stopping and restarting of the calculations as the person moves will also incur additional cpu demands.

4. Which Monte Carlo codes?

Some of the most widely used Monte Carlo codes do not transport neutrons [Kawrakow and Rogers, 2000, Salvat et al., 2006] so they will not be useful for online dosimetry in mixed neutron-gamma fields. There are, however, several well established codes that do neutron and photon Monte Carlo transport, including MCNP6 [Pelowitz, 2013], MCNPX [Pelowitz, 2005], GEANT 4 [Allison et al., 2016], PHITS [Sato et al., 2013] and FLUKA [Battistoni et al., 2007]. Each of these is established as being able to produce results with acceptable accuracy, though all can produce poor results when not in the hands of an expert user [Siebert et al., 2006, Gualdrini et al., 2008].

All these codes can be used in complex geometries and with voxel phantoms, so in principle online dosimetry could use any of the codes that are capable of transporting neutrons. They are all relatively similar in terms of computational speed, except where the use of mesh phantoms is concerned[5]:

- Geant 4 took about 1-30 minutes to achieve 2% uncertainty for photons of varying energy, and 2-30 hours for neutrons, depending on the neutron energy
- PHITS was 3-20 times slower than Geant4 for photons and electrons but 2-8 times faster for neutrons
- MCNP6 required run times 3-4 times longer than Geant4

These data are for a single 2.8 GHz processor using a single core, so acceleration is possible. However, it can be anticipated that by the time ICRP adopt mesh phantoms on radiation protection, the codes will all be able to deal with them in an efficient manner.

[3] On a Lenovo ThinkPad with an Intel® Core™ i7-770HQ

[4] Again, on a Lenovo ThinkPad with an Intel® Core™ i7-770HQ. When using the default settings, initializing the voxel phantom takes MCNP 6.1 about 60 s and MCNP 6.2 about 45 minutes, but workarounds are readily available.

[5] http://www.icrp.org/docs/TG103%20Report%20for%20Consultation%2020180906.pdf

5. Can calculations be accelerated?

Variance reduction methods can be applied effectively when calculating the field at a location, with there being many options within the available codes. Some of the methods are definitively two step, MCNP 'weight windows' being a prime example: a Monte Carlo run is first performed to determine the optimum weight windows map, before then applying this map to the subsequent full simulation. Consequently, it would be very complex to apply this in real time.

An additional difficulty for online dosimetry, where Monte Carlo proceeds in real time as the person moves through the geometry, is that the variance reduction would need to be continually reoptimised in synchronicity with the concurrent motion of the tallying volume within the model. This may limit the options for accelerating the calculations by using variance reduction methods. However, one option might be to surround the tallying volume with layers of 'dummy cells', of increasing importance with proximity to the tally, that move with it. Such an arrangement could be controlled by automatically editable subsidiary files that are external to the main MCNP input file, so that the variance reduction remains relatively optimized as the person moves.

Accelerated processing using graphics processing units (GPU) that are being investigated in PODIUM WP4 are currently limited to photons/electrons because they are only implemented in the Penelope code which does not transport neutrons, and the memory requirements of neutron cross sections cannot be applied when using GPU.

Using multiple cores in PC clusters can significantly accelerate calculations, and there are currently such clusters with large numbers of cores. If MCNP can be configured so that it can run a calculation spread across multiple cores, then the accelerations required for modelling $H^*(10)$ and $H_p(10)$ in real time seem feasible. It would perhaps be more realistic to run computations on a single core as a person moves through the geometry, opening a new calculation on a different core as the person moves. Real time calculations could then be achieved, albeit with a time delay for the calculation for each new position/orientation mapped. If the result for the dose was delivered after the shift was completed, that delay would not be a problem, assuming that the ALARP principle were being followed in the workplace.

6. Summary and conclusions

PODIUM has demonstrated that the look-up table approach for mixed fields is feasible. However, it was recognized from the outset that neutron effective doses could not be modelled in real time in complex geometries using voxel phantoms in the Monte Carlo model. This deliverable has shown that the computational requirements look feasible for the real-time calculation of the operational quantities, though it is acknowledged that neither $H_p(10)$ nor $H^*(10)$ provide adequate estimates of risk in all circumstances. Taken in isolation, the computational advances for real time online dosimetry estimations of effective dose look feasible if computations can be efficiently spread across many cores. Even if the computation cannot be split between multiple cores efficiently, then the use of individual cores for each location/orientation combination should be eminently feasible, even if it does not deliver real time results. However, whilst they are computationally feasible, fundamental difficulties still exist in applying the correct w_R in such calculations.

The conceptual mis-match between effective dose and what is feasible in Monte Carlo looks hard to resolve without either: changes to the definition of the protection quantity; or enhancements in the Monte Carlo codes that enable them to weight the dose deposited by a given particle by a factor associated with the energy and type of the particle that entered the body. This problem seems harder to resolve than the computing power issues.

7. References

ALLISON, J., AMAKO, K., APOSTOLAKIS, J., ARCE, P., ASAI, M., ASO, T., BAGLI, E., BAGULYA, A., BANERJEE, S., BARRAND, G., BECK, B. R., BOGDANOV, A. G., BRANDT, D., BROWN, J. M. C., BURKHARDT, H., CANAL, P., CANO-OTT, D., CHAUVIE, S., CHO, K., CIRRONE, G. A. P., COOPERMAN, G., CORTÉS-GIRALDO, M. A., COSMO, G., CUTTONE, G., DEPAOLA, G., DESORGHER, L., DONG, X., DOTTI, A., ELVIRA, V. D., FOLGER, G., FRANCIS, Z., GALOYAN, A., GARNIER, L., GAYER, M., GENSER, K. L., GRICHINE, V. M., GUATELLI, S., GUÈYE, P., GUMPLINGER, P., HOWARD, A. S., HŘIVNÁČOVÁ, I., HWANG, S., INCERTI, S., IVANCHENKO, A., IVANCHENKO, V. N., JONES, F. W., JUN, S. Y., KAITANIEMI, P., KARAKATSANIS, N., KARAMITROS, M., KELSEY, M., KIMURA, A., KOI, T., KURASHIGE, H., LECHNER, A., LEE, S. B., LONGO, F., MAIRE, M., MANCUSI, D., MANTERO, A., MENDOZA, E., MORGAN, B., MURAKAMI, K., NIKITINA, T., PANDOLA, L., PAPROCKI, P., PERL, J., PETROVIĆ, I., PIA, M. G., POKORSKI, W., QUESADA, J. M., RAINE, M., REIS, M. A., RIBON, A., RISTIĆ FIRA, A., ROMANO, F., RUSSO, G., SANTIN, G., SASAKI, T., SAWKEY, D., SHIN, J. I., STRAKOVSKY, I. I., TABORDA, A., TANAKA, S., TOMÉ, B., TOSHITO, T., TRAN, H. N., TRUSCOTT, P. R., URBAN, L., UZHINSKY, V., VERBEKE, J. M., VERDERI, M., WENDT, B. L., WENZEL, H., WRIGHT, D. H., WRIGHT, D. M., YAMASHITA, T., YARBA, J. & YOSHIDA, H. 2016. Recent developments in Geant4. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* 835**,** 186-225.

BATTISTONI, G., CERUTTI, F., FASSO, A., FERRARI, A., MURARO, S., RANFT, J., ROESLER, S. & SALA, P. The FLUKA code: Description and benchmarking. AIP Conference proceedings, 2007. AIP, 31-49.

DIETZE, G., BARTLETT, D. T., COOL, D. A., CUCINOTTA, F. A., JIA, X., MCAULAY, I. R., PELLICCIONI, M., PETROV, V., REITZ, G. & SATO, T. 2013. ICRP, 123. Assessment of radiation exposure of astronauts in space. ICRP Publication 123. *Ann ICRP,* 42**,** 1-339.

ENDO, A. The Operational Quantities and New Approach by ICRU. Proceedings of the Third International Symposium on the System of Radiological Protection. Seoul, Korea, 2015. 20-22.

GUALDRINI, G., TANNER, R., AGOSTEO, S., POLA, A., BEDOGNI, R., FERRARI, P., LACOSTE, V., BORDY, J.-M., CHARTIER, J.-L. & DE CARLAN, L. 2008. Analysis of the CONRAD computational problems expressing only stochastic uncertainties: neutrons and protons. *Radiation protection dosimetry,* 131**,** 7-14.

ICRP 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. *Annals of the ICRP,* 37

ICRP 2009. Adult Reference Computational Phantoms. ICRP Publication 110. . *Ann. ICRP* 39.

ICRP 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. Publication 116. . *Ann. ICRP* 40.

KAWRAKOW, I. & ROGERS, D. 2000. The EGSnrc code system: Monte Carlo simulation of electron and photon transport.

PELOWITZ, D. B. 2005. MCNPX user's manual version 2.5. 0. *Los Alamos National Laboratory,* 76.

PELOWITZ, D. B. 2013. MCNP6 user's manual version 1.0. *Vol. LA-CP-13-00634, Rev. 0*.

SALVAT, F., FERNÁNDEZ-VAREA, J. M. & SEMPAU, J. PENELOPE-2006: A code system for Monte Carlo simulation of electron and photon transport. Workshop Proceedings, 2006.

SATO, T., NIITA, K., MATSUDA, N., HASHIMOTO, S., IWAMOTO, Y., NODA, S., OGAWA, T., IWASE, H., NAKASHIMA, H. & FUKAHORI, T. 2013. Particle and heavy ion transport code system, PHITS, version 2.52. *Journal of Nuclear Science and Technology,* 50**,** 913-923.

SCHUHMACHER, H., BARTLETT, D., BOLOGNESE-MILSZTAJN, T., BOSCHUNG, M., COECK, M., CURZIO, G., D'ERRICO, F., FIECHTNER, A., KYLLÖNEN, J.-E., LACOSTE, V., LINDBORG, L., LUSZIK-BHADRA, M., REGINATTO, M., TANNER, R. & VANHAVERE, F. 2006. Evaluation of individual dosimetry in mixed neutron and photon radiation fields (EVIDOS). Braunschweig: PTB

SIEBERT, B. & SCHUHMACHER, H. 1995. Quality factors, ambient and personal dose equivalent for neutrons, based on the new ICRU stopping power data for protons and alpha particles. *Radiation Protection Dosimetry,* 58**,** 177-183.

SIEBERT, B., TANNER, R., CHARTIER, J.-L., AGOSTEO, S., GROßWENDT, B., GUALDRINI, G., MÉNARD, S., KODELI, I., LEUTHOLD, G. & PRICE, R. 2006. Pitfalls and modelling inconsistencies in computational radiation dosimetry: lessons learnt from the QUADOS intercomparison. Part I: Neutrons and uncertainties. *Radiation protection dosimetry,* 118**,** 144-154.

YEOM, Y. S., CHOI, C., HAN, H., LEE, H., SHIN, B., NGUYEN, T. T., HAN, M. C., LEE, C. & KIM, C. H. 2019a. Dose coefficients of mesh-type ICRP reference computational phantoms for idealized external exposures of photons and electrons. *Nuclear Engineering and Technology,* 51**,** 843-852.

YEOM, Y. S., CHOI, C., HAN, H., SHIN, B., NGUYEN, T. T., HAN, M. C., KIM, C. H. & LEE, C. 2019b. Dose coefficients of mesh-type ICRP reference computational phantoms for external exposures of neutrons, protons, and helium ions. *Nuclear Engineering and Technology*.