

## Radiological characteristics of charged particle interactions in the first clay-nanoparticle dichromate gel dosimeter

ML Taylor<sup>1,2†</sup>, T Maeyama<sup>3</sup>, N Fukunishi<sup>3</sup>, KL Ishikawa<sup>4,5,6</sup>, K Fukasaku<sup>4,7</sup>, T Furuta<sup>9</sup>, S Takagi<sup>4,8</sup>, S Noda<sup>4,9</sup>, R Himeno<sup>4,9</sup> and S Fukuda<sup>10</sup>

<sup>1</sup> RMIT University/School of Applied Sciences, Melbourne, Australia

<sup>2</sup> Peter MacCallum Cancer Centre/Physical Sciences, Melbourne, Australia

<sup>3</sup> RIKEN/Nishina Centre for Accelerator-Based Science, Wako, Japan

<sup>4</sup> RIKEN/Computational Science Research Program, Wako, Japan

<sup>5</sup> The University of Tokyo/Department of Nuclear Engineering and Management, Graduate School of Engineering, Tokyo, Japan

<sup>6</sup> The University of Tokyo/Photon Science Centre, Graduate School of Engineering, Tokyo, Japan

<sup>7</sup> Himon'ya Hospital, Department of Neurosurgery, Tokyo, Japan

<sup>8</sup> The University of Tokyo/Department of Mechanical Engineering, Graduate School of Engineering, Tokyo, Japan

<sup>9</sup> RIKEN/Advanced Centre for Computing and Communication, Wako, Japan

<sup>10</sup> National Institute of Radiological Sciences / Research Centre for Charged Particle Therapy, Chiba, Japan

E-mail: michael.taylor@rmit.edu.au

**Abstract.** The incorporation of clay nanoparticles into gel dosimeters shows promise for significant diffusion reduction – but to what extent does the presence of the nano-clay influence charged particle interactions and, in particular, what is the impact on water equivalence? In this work, we quantify the radiological characteristics of electron, proton and carbon ion interactions in the RIKEN dichromate nanoclay gel and specifically evaluate the water equivalence over a broad energy range. Results indicate that the radiological properties are sufficiently representative of tissues that this low-diffusion gel could readily be used for validation of complex dose distributions. Electron and proton ranges are within 1 % of those in water. Mean effective atomic numbers for electron interactions in the range 10 keV – 10 GeV are within 1 % of those of water which, coupled with the similar mass density, ultimately means the overall impact on dose distributions is not great. The range of C<sup>6+</sup> ions in the nanoclay gel is closer to that of water (< 4 %) than a common polymer gel dosimeter (< 7 %), though experimentally measured R<sub>1</sub> values indicate an over-response at low doses.

### 1. Introduction

Contemporary radiotherapy involves increasingly small fields and often complex dose distributions<sup>1</sup> and, within this context, gel dosimetry possesses many advantages over other dosimetric methods (1). Polymer gels have reduced diffusion when compared to ferrous-sulphate (Fricke) based formulations, but exhibit greater artefacts (due mostly to Mie scattering) when imaged with modern optical readout techniques compared to ferrous-sulphate gels, which are amenable to spectrophotometric approaches



(2). A novel alternative currently being explored is dichromate gel dosimetry, with a clay nanoparticle additive as a diffusion suppressant (3). This, however, raises the immediate question as to the radiological influence of the nano-clay and, particularly, the extent of deviation from water equivalence. In this work, we investigate the fundamental characteristics of charged particle (electron, proton and Carbon ions) interactions and quantify any differences to water and tissue.

## 2. Methods

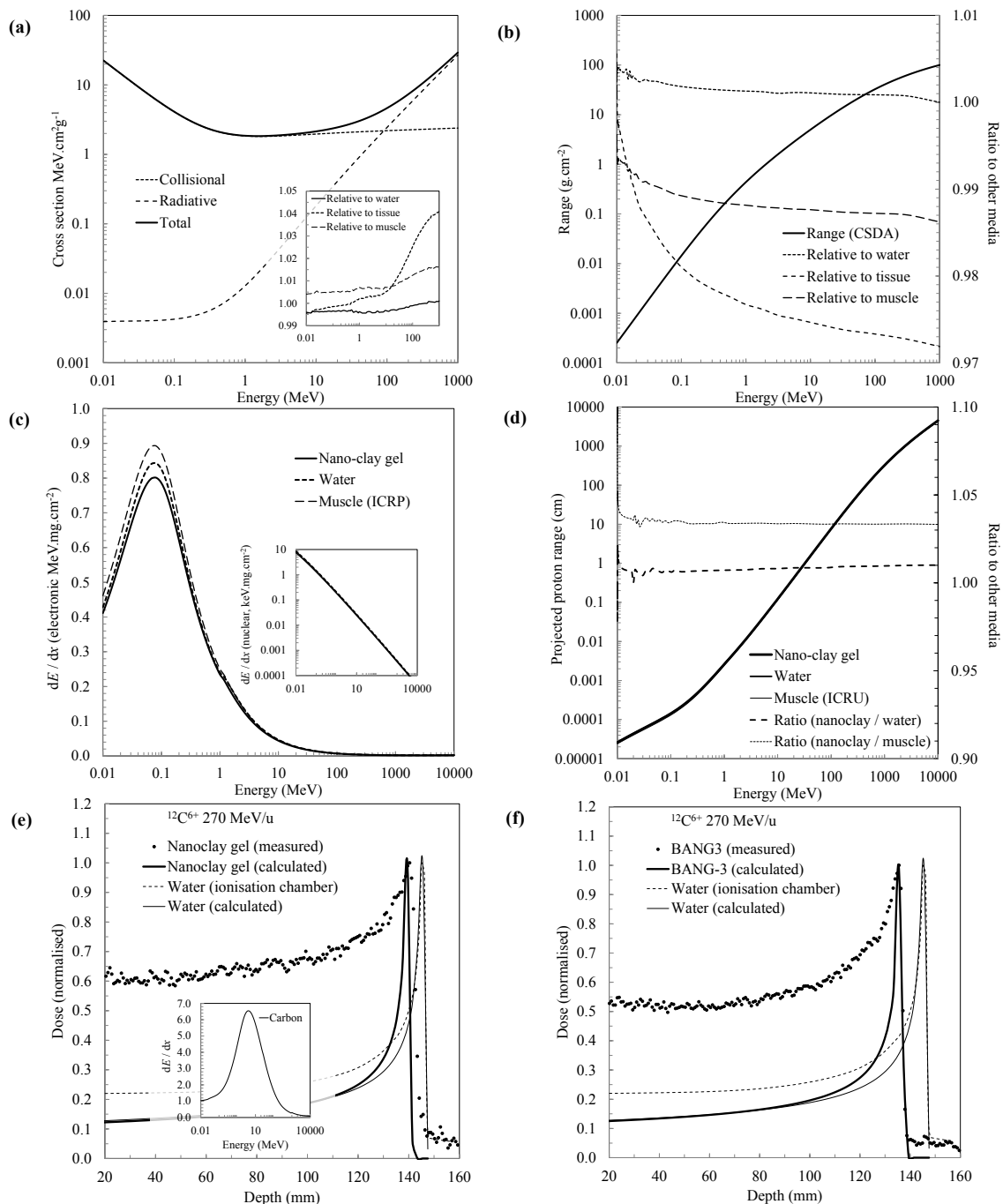
A range of calculations and comparisons have been made for electron, proton and Carbon ion interactions. For electron interactions: (i) Mean energy-dependent effective atomic numbers have been calculated *via* the Taylor approach (4-7); (ii) Collisional interaction cross sections have been presented as a function of kinetic energy using the standard Bethe-Bloch (8-10) approach recommended by the ICRU (11); (iii) Radiative interaction cross sections have been determined using the combined method of Seltzer and Berger (12, 13); (iv) Continuous slowing down approximation (CSDA) ranges have also been calculated. For proton interactions: (i) electronic and (ii) nuclear stopping powers have been determined, and (iii) projected proton ranges have been computed according to Ziegler (14, 15). Equivalent calculations have also been undertaken for Carbon ions. Example dose distributions have also been computed. In each case, comparisons are made to water and ICRU-defined tissues. Experimental measurements for  $C^{6+}$  ion beams (Heavy Ion Medical Accelerator, NIRS Japan) are also shown, with readout undertaken *via* MRI (1.5T Philips Achieva).

## 3. Results

The mean effective atomic number for electron interactions in the nanoclay gel over the range 10 keV – 10 GeV are presented in Table 1, along with other media (relevant to medical physics) for comparison. Stopping powers are shown in Figure 1(a) for electron interactions, with the ratio to water presented as an insert. The continuous slowing down approximation ranges for electrons in the nanoclay gel are presented in Figure 1(b); plotted as dashed lines against the right axis is the ratio of ranges in gel to water and tissue. A depth-dose distribution of 1 MeV electrons in the nanoclay gel (not shown) indicates a shift in  $d_{\max}$  of approximately 0.2 mm relative to water. Figure 1(c) shows that the electronic stopping power for proton interactions is lower than that for water (by a maximum of 5 %) while nuclear stopping powers, which comprise a small fraction of the total stopping power, are similar. Proton ranges are within several percent of those in water; see Figure(d). Figure 1(e) indicates that the range of 270 MeV/u  $C^{6+}$  ions in nanoclay gel is within 6 mm of that of water, compared to 10 mm for a common polymer gel formulation (BANG-3). Both measured and calculated data are shown. The  $R_1$  values indicate an over-response to the high LET radiation in low-dose regions.

**Table 1.** Mean effective atomic numbers for the partial and total electron interaction processes; the spread of values over the 10 keV – 10 GeV range is indicated by the standard deviation. Along with the nanoclay gel, data for water, tissues and other dosimeters are provided for comparison.

$\overline{Z}_{\text{eff}}$	Radiative	$\sigma$	Collisional	$\sigma$	Total	$\sigma$
Nanoclay gel	4.605	0.113	3.659	0.462	3.732	0.534
Water	4.569	0.112	3.623	0.465	3.696	0.534
Tissue (16)	4.613	0.108	3.688	0.416	3.772	0.502
Bone (16)	5.757	0.156	4.273	0.231	4.552	0.562
BANG gel (17)	4.598	0.104	3.709	0.418	3.784	0.493
TLD-100 (4)	6.653	0.066	6.200	0.204	6.230	0.237
$R$ (nanoclay/water)	1.008	-	1.010	-	1.010	-



**Figure 1** (a) Collisional, radiative and total electron interaction cross sections in the nanoclay gel; data relative to water and human tissues are provided as an insert. (b) The continuous slowing down approximation range of electrons (left axis); the dashed lines indicate the ratio of ranges in gel to those in water and tissue (right axis). (c) Proton electronic stopping powers plotted alongside those for water and muscle tissue; the insert indicates the nuclear stopping power. (d) Proton range as a function of energy (left axis; note these effectively overlap); the dashed lines indicate the ratio of ranges in gel to those in water and tissue (right axis). (e) The depth dose profile corresponding to 270 MeV/u  $\text{C}^{6+}$  ions in the nanoclay gel, both measured and calculated. For comparison, an equivalent profile in water (measured with an ionisation chamber) is also provided, demonstrating a 6 mm difference in range. The insert indicates the total (electronic and nuclear) stopping power for Carbon ions in the nanoclay gel. (f) For comparison to the nanoclay gel, we have also measured (and calculated) depth dose curves in BANG gel. The discrepancy compared to water is more pronounced in this case (10 mm).

#### 4. Conclusions

The nanoclay gel exhibits broadly similar radiological properties to water, tissue and other dosimeters over the keV – GeV range for electron, proton and Carbon interactions. The addition of clay nanoparticles raises the effective atomic number only at the sub-percent level and the mass density is not significantly different to water; consequently, resultant dose distributions are not greatly impacted. By comparison, the difference in effective atomic number for the BANG gel formulation is greater relative to water (due mostly to collisional interactions). Ultimately, the results suggest that the formulation could be readily employed for validation of phantom-mapped patient plans.

#### 5. Acknowledgments

Research support: (i) Research and Development of the Next-Generation Integrated Simulation of Living Matter (MEXT Next-Generation Supercomputer Project, Japan), (ii) RIKEN President's Discretionary Fund (Strategic Programs for R&D), (iii) Postdoctoral researcher program of RIKEN & MEXT (JSPS) KAKENHI (24760725). We thank the HIMAC staff for providing beamtime.

#### 6. References

- [1] Taylor M *et al* 2011 *Acta. Oncol.* **50** 483-508
- [2] Baldock C *et al* 2010 *Phys. Med. Biol.* **55** R1-63
- [3] Maeyama T *et al* 2012 *IFMBE Proc.* **39** 1183-6
- [4] Taylor M 2011 *Nucl. Instrum. Methods Phys. Res. B* **269** 770-3
- [5] Taylor M *et al* 2009 *Radiat. Res.* **171** 123-6
- [6] Taylor M *et al* 2012 *Med. Phys.* 2012 **39** 1769-78
- [7] Taylor M *et al* 2008 *Australas. Phys. Eng. Sci. Med.* **31** 131-8
- [8] Bethe H 1930 *Ann Physik* **5** 325
- [9] Bethe H 1932 *Zeitschrift für Physik* **76** 293-9
- [10] Bloch F 1933 *Annalen der Physik* **408** 285-320
- [11] ICRU 1984 ICRU Report No. 37 (Washington, DC)
- [12] Seltzer S and Berger M 1985 *Nucl. Instr. Meth. Phys. Res. B* **12** 95-134
- [13] Seltzer S and Berger M 1986 *Data Nucl Data Tables* **35** 345-418
- [14] Ziegler J and Biersack J 1985 *The stopping and range of ions in matter* (Pergamon Press)
- [15] Ziegler J *et al* 2010 *Nucl. Instr. Meth. Phys. Res. B* **268** 1818-23
- [16] ICRU 1989 Report No 44 (Bethesda, MD)
- [17] Zeidan O *et al* 2010 *Med. Phys.* **37** 2145-52