Calibrating Gate to match the RSP-HU curves of our CT scanner

Steven Court, Dec 2019

Aim

We need to calibrate the Gate MC simulations to our clinical set-up. One aspect of this is ensuring that the HU-density-material definitions in GATE reproduce the HU-RSP curve of our CT calibration. This document summarizes the first attempt at this.

CT calibration: Through some method (DECT, stoichiometric method) RSP values are assigned to the HU values of the CT scanner. This RSP-HU curve is what is entered into the TPS for dose calculations. There will be 2 curves (for small and large phantoms), since beam hardening affects the shape of the curves, especially at higher HUs.

Gate: The Schneider2000 database is provided with GATE. There are 2 input files that will define our CT calibration: in *Schneider2000DensitiesTable.txt* HU values are assigned a physical density (g/cm^3); and in *Schneider2000MaterialsTable.txt* HU ranges are assigned to materials, with these materials specified by their atomic composition. It is possible to define new materials in the *GateMaterials.db* file. They can be defined using their elemental composition or as combinations of other materials in the *GateMaterials.db* file. RSP values are not an input parameter into the Gate simulation.

Method

Since the RSP values cannot be changed directly in Gate we must find other parameters to alter. One method to do this is described in Verburg2016 in which they match stopping powers by adjusting the densities of materials through Eq. 5 in their paper:

$$\rho_i = P_i \ \rho_w \ \frac{S_w}{S_i} \qquad (1)$$

where P_i is the proton stopping power relative to water obtained in the stoichiometric calibration for a material with HU=*i*, S_w is the mass stopping power of water used in Gate, S_i is the mass stopping power of the material in Gate, and ρ_w is the density of water (1.0 g/cm^3 in Gate).

In brief, the materials used in the CT calibration are simulated in Gate so as to extract S_m, then their "calibrated densities" are calculated using the above equation. A selection of these materials are then used to generate new versions of the two Schneider2000 tables to be used in our simulations. Note that nothing actually needs to be simulated, but volumes of each material must be added to a Gate world. The EmCalculatorActor can then be used to extract the stopping power information for every material present in the simulation.

Procedure

1. Obtain the CT calibration data to be reproduced. This will include the elemental composition of the materials used (i.e. WoodardWhite tissues), their physical densities, plus the HU-RSP curve generated for these tissues.

2. Add the materials to the GateMaterials.db file. (The "make_WW_tissues.py" script can be used to generate the appropriate Gate commands for each material, which can be copied into the .db file. The script was written specifically for the formatting of the WW tissues I was given – check that it is still appropriate, for example that the elements are listed in the correct order.)

3. Create volumes of each material within a Gate simulation. (The "make_WW_tissue.py" script will also generate a file containing the relevant gate commands to do this that you can copy and paste into your main .mac file).

4. Confirm the correct ionization potential of water is being used. Gate will use a default value of 68.9984 eV but the calibration data we used was for a value of 78 eV. The required command is "/gate/geometry/setIonisationPotential Water 78 eV".

5. Add the EmCalculatorActor to the simulation and simulate a single particle. Note that it does not matter what you simulate, this actor will only produce the data for the particle and energy assigned to it, not to the properties of the actual source used in the simulation. RSPs should be invariant to energy, but use a mid-energy such as 155 MeV.

```
655 /gate/actor/addActor    EmCalculatorActor       emcalc
656 /gate/actor/emcalc/save                        output/emcalc.txt
657 /gate/actor/emcalc/setParticleName            proton
658 /gate/actor/emcalc/setEnergy                  155 MeV
```

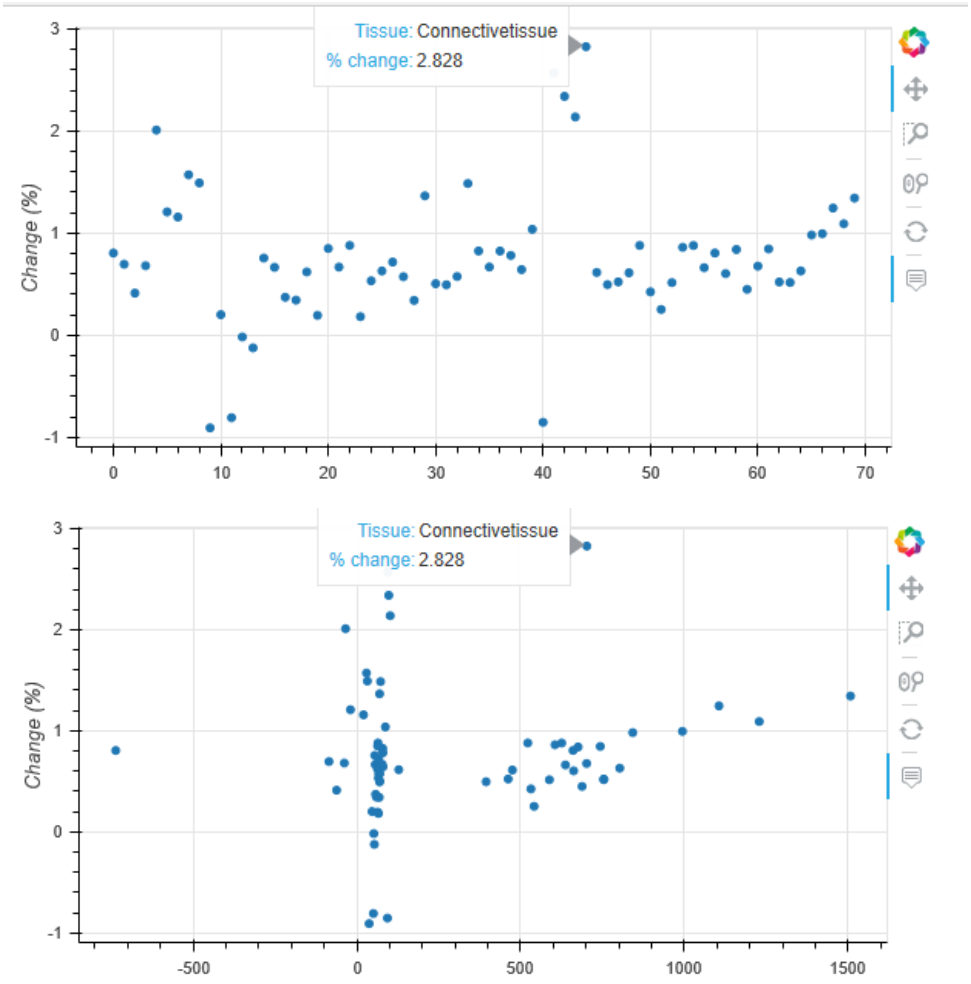
6. Calibrate the density of each material using Eq (1). The "calibrate_densities.py" script will read in the CT calibration RSP values (P_i) along with the S_w and S_i values from the output generated by the EmCalculatorActor. It will output a csv file listing the tissue, it's HU value and density.

7. Use a selection of these tissues and their calibrated densities to generate new versions of the Schneider2000 files. It might take some experimentation to figure out exactly what should be included for optimal results.

Results

The UCLH2019DensitiesTable_v1.txt and UCLH2019MaterialsTable_v1.txt are the result of me carrying out this procedure.

The figure below shows how much the density of each WW tissue had to be tweaked to achieve the RSP match. The mean and median changes are 0.76% and 0.67%, respectively. The max and min changes required were 2.83% and -0.91%, respectively. (Top figure shows each tissue by its index and bottom shows each tissue by its HU value). (Oops - maybe the sign is wrong for these % values).



Checking the EmCalculatorActor output

Just to be sure that what we were getting from the EmCalculatorActor was sensible I also calculated the RSP value for a few tissues by simulating an experimental measurement. To do this I created a 20x20x20 cm block of water and irradiated it with a 155 MeV beam to produce high resolution IDD curves. From these I calculated the range as the distal $R_{80}{}^{w}$ value. I then added some thickness (T=5cm) of material m directly under the surface of the water and measured the range, $R_{80}{}^{m}$, under this setup. I then calculated the RSP of material m via:

$$RSP_m = 1 + \frac{R_{80}{}^{w} - R_{80}{}^{m}}{T} \qquad (2)$$

The table below shows the agreement with this method and the values obtained from the EmCalculatorActor. Values between the methods agreed to 0.75%.

Tissue	RSP EmCalculatorActor	RSP Equation (2)	Diff (%)
Adiposetissue3	0.9588	0.966	-0.75
Braingraymatter	1.0495	1.048	0.14
Corticalbone	1.7198	1.714	0.3%

Notes

(1) I used the RSP values from the fitted RSP-HU curve (not the calculated values) for all WW tissues. Might want to check if this makes any difference. The differences between the calculated and fitted values ranges from -2% to 2% (but as high as 13% for the "Lung Inhale 0.2" insert for the CIRS phantom. The CIRS data was NOT used in the current calibration).

(2) Note that if you make an error specifying the elemental composition of a material in the GateMaterials.db file, Gate will auto-normalize this but give you no warning that it has done so. I should alter the script to confirm this doesn't happen.

(3) The RSP of materials should be energy independent for therapeutic energies (Abbema2018). I checked this for RibBone and the RSP varied by only 0.34% going from 100 MeV to 200 Mev.

(4) I checked for Air, Water and RibBone and changing the physics list did not affect any of the stopping powers given by EmCalculatorActor. To generate the RSP data we just need to put all the materials we want somewhere in the world and run a simulation of whatever.

(5) The *EmCalculatorActor* provides EM, nuclear and total mass stopping powers (along with density, e-density and ionization potential). Note that the nuclear part is always zero for therapeutic proton energies (it is not the nuclear interactions but the electromagnetic interactions between the proton and the nuclei). This 'nuclear' contribution will increase with increasing particle mass and decreasing energy but was zero in all my simulations.

(6) The ionization potential of water is important (Bragg's additivity rule gives 69eV, ICRU 73 says 78eV while Abbema2018 say 73.2eV matches their data). Our data and simulations used a value of 78 eV.

(7) Schneider2000DensitiesTable only contains 10 points. How does it interpolate the densities between these?

References

Verburg2016: *Automated Monte Carlo Simulation of Proton Therapy Treatment Plans;* Technology in Cancer Research; 15(6); 2016.

Abbema2018: *High accuracy proton relative stopping power measurement;* Nuclear Inst. And Methods in Physics Research B; 436; 2018.