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

Steven Court, Jan 2021

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 scanner. This document summarizes this procedure.

CT calibration: Through some method (i.e. stoichiometric calibration) relative stopping power (RSP) values are assigned to the HU values of the CT scanner. This HU-RSP curve is what is entered into the TPS for dose calculations. There will be at least 2 curves per scanner (e.g. head/body curves), since beam hardening affects the shape of the curves, especially at higher HUs.

Gate: The Schneider2000 materials 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 elemental 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 present in the file. Note that RSP values are not an input parameter to Gate.

Method

Since the RSP values cannot be changed directly in Gate we must use other parameters to perform the matching. One method to do this is described in Verburg2016 in which they match the stopping powers in their CT calibration to those in their simulation simply by adjusting the physical densities of the materials in Gate via:

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

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 in Gate (1.0 g/cm^3).

In brief, the materials used in the CT calibration are simulated in Gate so as to extract S_i then their “calibrated densities” are calculated using the above equation. A selection of these materials is 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 need to be added to the Gate world volume. 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 matched. This will include the elemental composition of the materials used (i.e. WoodardWhite tissues) and their physical densities, plus the HU-RSP calibration curve generated for these tissues by the CT scanner.

2. Add the material definitions to the GateMaterials.db file. The "make_tissues.py" script can be used to generate the appropriate Gate commands for each material, which can be copied into the "_base" db file provided. (Look at the example csv file for formatting – the names of the elements in this file must be specified correctly in the python script).

3. Create volumes of each material within a Gate simulation. The "make_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 simulation mac file (e.g. the RSP_EmCalcActor.mac file provided).

4. Confirm the same ionization potential of water is being used as in the original calibration. Gate will use a default value of 68.9984 eV but the calibration data we used assumed 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 doesn't 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 will be almost invariant with energy, but use a mid-energy such as 155 MeV. The stopping power data will be stored in the emcalc.txt file.

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

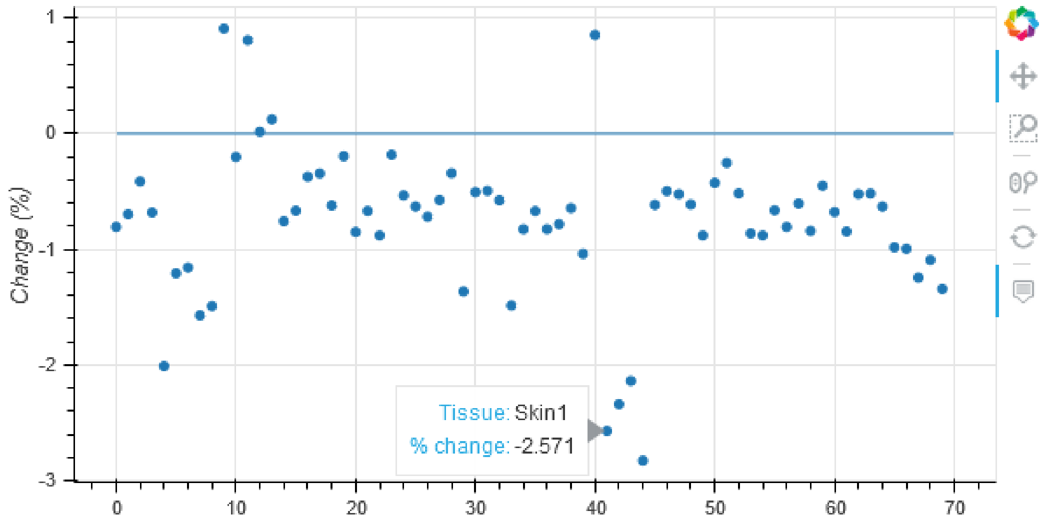
6. Calibrate the density of each material using Eq (1). The "calibrate_densities.py" script will read in the CT calibration RSP values (P_i) along with the S_w and S_i values from the output generated by the EmCalculatorActor. It will output a csv file containing the tissue, its HU value, its calibrated density as well as the original density and percentage change. The CT calibration data provided to this script must be a csv file in which the 1st column contains the tissue names, 2nd column the HU values, 3rd column the RSP values and the 4th column the physical densities (see example_RSPs_from_CT.csv).

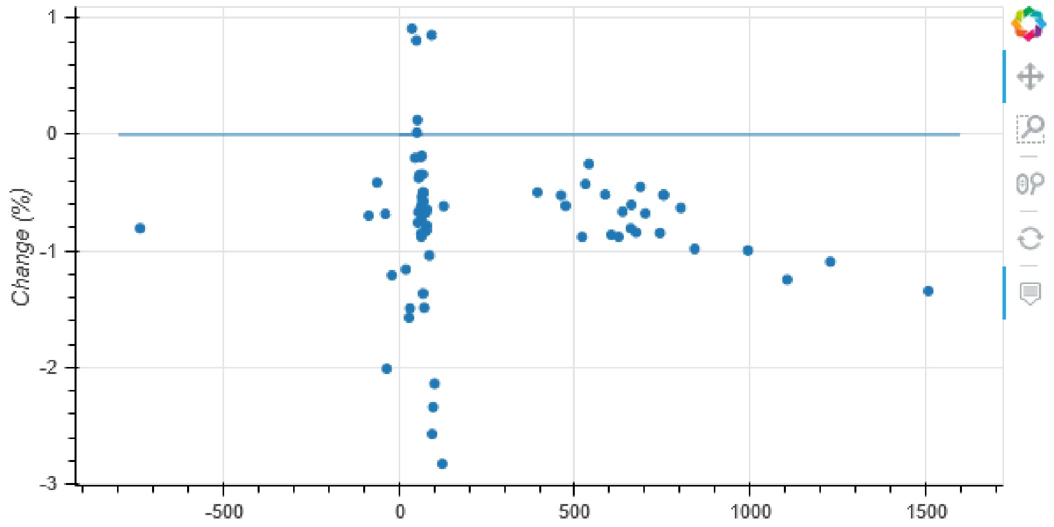
7. Use a selection of these tissues and their calibrated densities to generate new versions of the Schneider2000 files. It might take some experimentation to figure out exactly what should be included for optimal results.

Results

The UCLH2019DensitiesTable_v1.txt and UCLH2019MaterialsTable_v1.txt are the products of the procedure detailed here.

The figure below shows how much the density of each WW tissue had to be tweaked to achieve the RSP match. The vast majority were scaled down. The mean and median changes are -0.76% and -0.67%, respectively. The max and min changes required were 0.91% and -2.83%, respectively. (Top figure shows each tissue by its index and bottom shows each tissue by its HU value).





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. The make_tissues.py script will point this out though.

(3) The RSP of materials should be energy independent for therapeutic proton 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 the 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 Gate 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.