for graphite (and a number of other materials of dosimetric interest) using Geant4 in a range of clinical proton beams.
**Materials and Methods:** An application was developed using Geant4 (v9.6.p01) to score both dose and fluence spectra differential in energy for protons, alphas, deuterons and tritons at equivalent depths in water and graphite for a range of incident proton beams energies (60, 140 and 230 MeV). The variation of $k_{fl}$ with depth in graphite (with respect to water) was determined in two ways: (1) by integrating the stopping power data over binned fluence spectra for all charged particles (fluence scoring method), and (2) from the ratio of doses (dose scoring method), at equivalent depths in these materials. Fluence correction factors (or the 'water equivalence') of a number of other materials were also examined using these techniques.
**Results:** Fluence correction factors determined using both methods were found to be consistent. For graphite, $k_{fl}$, was found to be close to unity at the surface when only protons are considered and ~0.5% less than unity at shallow depths with all charged particles (due to contributions from short range alpha particles) at all energies. $k_{fl}$, was found to increase with depth up to a maximum of 1.2% (60 MeV), 2.4% (140 MeV) and 4.5% (230 MeV) just upstream of the Bragg peak region. Water equivalent plastics (WT1, PW, PWDT) designed for photon beams and polystyrene gave similar results at all energies (0.5%-1% up to the Bragg peak) whereas $k_{fl}$ ranged from 0.5% (60 MeV) to -1.5% (230 MeV) for polyethylene. A-150 was found to be the most water-equivalent material with $k_{fl}$ being close to unity at all energies and depths up to the Bragg peak.
**Conclusions:** The simulation results presented here indicate that water-equivalent depths of 0.6 cm (60 MeV), 3.0 cm (140 MeV) and 6.0 cm (230 MeV) are ideal reference depths for graphite calorimetry since the fluence correction vanishes. To avoid corrections larger than 1%, reference dosimetry should not be performed at water-equivalent depths larger than 9 cm in a 140 MeV beam and 15 cm in a 230 MeV beam. The observed difference between phantom materials warrant further research for tissue materials of importance in treatment planning and dose calculations in proton therapy. The effect of beam modulation will also be studied in future work.

**OC-0160**

**Beam halo measurement in proton beams: experimental challenges and lessons for dose modelling of pencil beams**

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**Purpose/Objective:** A proton beam deposits a non-negligible amount of dose off the beam axis due to particles scattered at high angles by multiple coulomb scattering or nuclear interactions. Modelling such an effect is particularly challenging for proton pencil beams, which require small field dosimetry and a setup highly sensitive to changes in the deposited dose, spanning several orders of magnitude. We developed an experimental protocol for measuring the lateral distribution of a clinical proton pencil beam, including effects due to particles scattered at large angle because of nuclear interactions or high-energy elastic scattering. Our method is particularly effective with small pencil beams as those used in intensity modulated proton therapy (beam sigma less than 5 mm), and can be easily generalized to other facilities.
**Materials and Methods:** We measured the dose deposited off axis up to a distance of 6 cm from the beam centre, for different depths in water and different energies. We used a small ionization chamber (PTW PinPoint 31014) in a water phantom in accordance to dosimetry protocols for clinical fields. We estimated chamber effects from simulations and included them in the analysis. To avoid any interference due to materials other than water in the beam path, we placed the chamber directly in water and delivered the beam vertically on the water surface (no entrance window). We optimized our analysis considering the high dynamic range of the data (covering four orders of magnitude), and tested it on MC simulations to study possible biases.
**Results:** Three regimes are visible in our data: a first contribution dominant within 1.5 cm from the beam axis, made of particles scattered at low angles from the beam, which we modelled as a Gaussian distribution, as commonly done in treatment planning systems; a second contribution, dominant between 2 to 4 cm from the beam axis, made of particles undergoing nuclear or multiple elastic scattering interactions, which we modelled as a Gaussian distribution too; and a long-radii tail, made of particles scattered at high angles (due mainly to nuclear interaction processes), which we modelled as an exponential tail based on physical arguments and MC simulations. The second contribution increases with depth reaching up to 6% of the total dose distribution, while the third is below 1%. We estimated all components within 5% uncertainty for all energies and depth considered.
**Conclusions:** We designed an experimental setup with an air-vented, small volume ionization chamber allowing a precise estimate of the beam width and lateral spread of a proton pencil beam. Our method has many advantages over films or CCD, used by other institutes, since it is more sensitive to the tails, more precise, and more robust with respect to experimental uncertainties. To achieve even better conformity, proton therapy requires small beam sizes and high precision beam models; our method provides a way to achieve such a goal with an easy experimental setup.

**OC-0161**

**'End to end' validation of a Monte Carlo code for independent dose calculation in a proton pencil beam scanning system**

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**Purpose/Objective:** To validate the Monte Carlo (MC) model of a proton pencil beam scanning (PBS) system in clinical use in our ProtonTherapy (PT) Center.
**Materials and Methods:** TOPAS [1] (ver12) was used to simulate our proton beam delivery system. The model was obtained starting from the commissioning measurements. Spot shape and size, divergence, integral-depth-dose curve of the beam were studied as a function of energy and gantry angle. Absolute dose calibration was achieved based on ionization chamber and Faraday cup measurements to describe the number of protons per monitor unit (MU) as a function of the beam energy. In this way the results were scored in terms of absolute dose and the comparisons between Treatment Planning System (TPS), MC and measurements did not need renormalization. The TPS used in our center is XiO (Computerized Medical System Inc.). A method to convert XiO-DicomPlan to TOPAS input files was developed. The CT scanner was calibrated and four different cases of Head and Neck (H&N) tumors were simulated. These results were compared with TPS dose calculation and

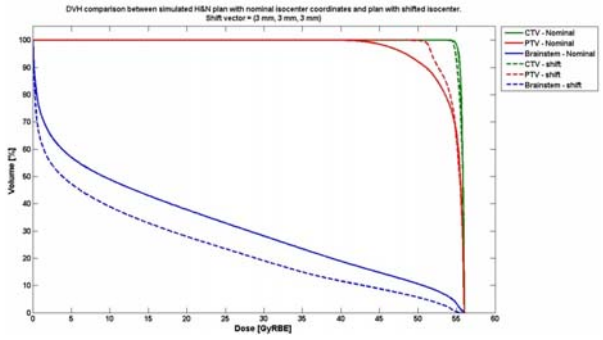
GAFCHROMIC film (EBT3) measurements in anthropomorphic phantoms.

**Results:** Comparing data both via gamma analysis method (3%, 3mm) and DVH comparison (between TPS and MC), a very good agreement between dose distributions estimated by MC, TPS and films was shown. In table are summarized the gamma analysis results.

| ID Plan | Gamma Analysis (3%,3mm) Percentage of Passing Rate | | |
|---|---|---|---|
| | MC vs TPS | MC vs Measurements | TPS vs Measurements |
| H&N1 | 96.95 | NA | NA |
| H&N2 | 99.03 | 97.54 | 97.57 |
| H&N3 | 99.34 | 93.50 | 92.22 |
| H&N4 | 98.03 | 97.73 | 98.95 |

Table: Gamma analysis results from MC, TPS and GAFCHROMIC comparison. For H&N1 Plan no measurements were available because it was delivered on a real patient. For this plan only TPS-MC comparison is available.

The main differences between MC and TPS were detected in high and low density structures (bone and air cavities) where differences between dose to medium and dose to water (as it is computed by TPS) are highlighted. In a single plan, where the PTV included bone structures (CTV was contoured in soft tissue), a 3mm displacement along axial, coronal and sagittal direction was simulated. In figure DVHs before and after the shift are shown.




It is clear that the CTV coverage is not affected and the homogeneity in the CTV is guaranteed even if a lower than prescribed dose to medium was detected in the bone of the reference dose distribution.

**Conclusions:** This work proposes a method to model in TOPAS a proton therapy PBS machine using commissioning measurements with no machine geometrical head description. This modeling lets the user to simulate a complete treatment plan having as the only input the DICOM file produced by the TPS. This gives the physicist a completely independent MC dose calculation algorithm. One of the most interesting features is that the dose distribution is given in terms of absolute dose and the comparison can be implemented with no dose-rescaling. It can be used to validate the dose distribution coming from TPS or, in a near future, as a patient-specific QA tool.

[1] Perl J et al. *TOPAS - An innovative proton Monte Carlo platform for research and clinical applications*. Med Phys. 2012;39(6818-6837).

[2] Soukup M. et al. *A pencil beam algorithm for intensity modulated proton therapy derived from Monte Carlo simulations*. Phys. Med. Biol. 50 (2005) 5089-5104.

**OC-0162**

**Dosimetric feasibility of intensity modulated proton therapy in a transverse magnetic field of 1.5 Tesla**

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**Purpose/Objective:** In proton therapy protons are used to deliver radiation to a target. This promises higher dose conformality in comparison with regular radiotherapy techniques. Intensity Modulated Proton Therapy (IMPT) is a form of proton therapy, in which a pencil beam is used to cover the target. Because image guidance has an increasing role in radiotherapy and MRI is a prime candidate for this imaging, the dosimetric feasibility of IMPT in a magnetic field of 1.5 T and the effect on the generated dose distributions compared to those at 0 T is evaluated, using Monte Carlo simulations.

**Materials and Methods:** To generate the IMPT plans, existing treatment planning software for the MR Linac was used with proton beamlets as input. Using the Monte Carlo software TOol for PArticle Simulation (TOPAS), proton beamlets were generated. First the interactions within a box of water were simulated, in order to analyze the shape of the Bragg Peak inside a 1.5 T magnetic field, compared to the one without a magnetic field. Next, three different sites were selected to generate IMPT plans for, based on DICOM data. The selected sites were a shallow and deep head-neck tumor and an artificial liver tumor. As input for the plans, beamlets from three intuitively selected gantry angles were generated, covering the target completely from every angle, both in a 0 T and 1.5T magnetic field. The generation of the plans was accomplished using dedicated, homemade software, based on an inverse optimization method. For all sites, the IMPT plans for a 0 T and a 1.5 T magnetic field were generated and analyzed, by comparison of the dose parameters and difference inside the target.

**Results:** For a simulated 150 MeV proton beam in a water phantom, the shift of the Bragg Peak due to the magnetic field was 1.14 cm, which is in accordance to the analytical solution. A Gaussian fit for the lateral dose profile at the Bragg Peak gave $\sigma$ = 0.36 cm both without and with a magnetic field. For the DICOM data, the dose distributions of the generated IMPT plans for two sites are shown in figures 1a and 1b and figures 1d and 1e. The mean dose difference is $\mu = -8.5 \times 10^{-3}$ Gy ($\sigma$ = 0.14 Gy) for the shallow head-neck target, $\mu$ = -0.17 Gy ($\sigma$ = 1.11 Gy) for the deep head-neck target (figure 1c) and $\mu$ = -0.34 Gy ($\sigma$ = 0.62 Gy) for the liver target (figure 1f). The DVHs of the target were similar and the dose to the OARs, except the body, was negligible (figure 1g,h).

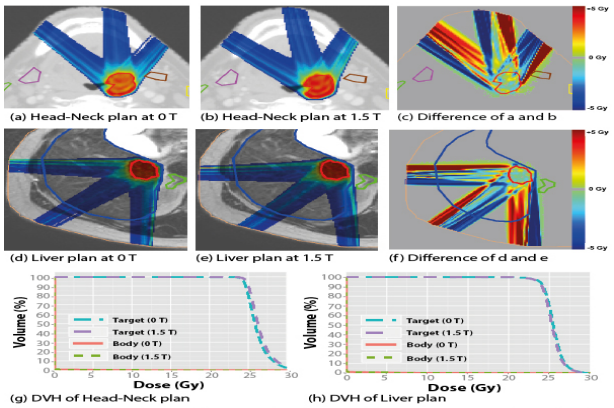


**Figure 1**. Transversal view of the IMPT plans for two different sites at 0T and 1.5T. Also, the difference of the dose distributions is shown. The target is shown in red in subfigures a-f. Subfigures g and h show the DVH for the target and body of both plans.
OAR's figure 1a-c: submandibular gland left (brown) and right (purple), parotid gland left (yellow) and right (green).
OAR's figure 1d-e: liver (blue), right adrenal (green).

**Conclusions:** This study shows that the generation of an IMPT plan in a magnetic field is feasible. The impact of the magnetic field is only on the curvature of the proton beam, which should be taken into account, but the resulting dose distributions are equivalent. It also shows that the introduced framework, which consists of Monte Carlo simulation