TORCH™: Voxel-Based Dosimetry for Radiopharmaceutical Therapy

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Voximetry, Inc. offers a software product called TORCH[1] that brings accuracy and simplicity to the otherwise complex task of performing dosimetry for radiopharmaceutical therapy (RPT) procedures. TORCH introduces automated workflows that reduce time, staffing, and required expertise to perform dosimetry without compromising the accuracy and precision needed to ensure safe and effective RPT procedures. This unique solution is made possible by carefully architecting dosimetry tasks such as image registration, contour propagation, kinetic modeling, and radiation transport to exploit the enormous parallel processing capabilities of GPUs. At the core of TORCH is our proprietary GPU-accelerated Monte Carlo (MC) radiation transport algorithm that will provide superior dosimetric accuracy compared to existing dosimetry products, so that dosimetry can be used as a predictive biomarker for toxicity and tumor response for each individual patient.

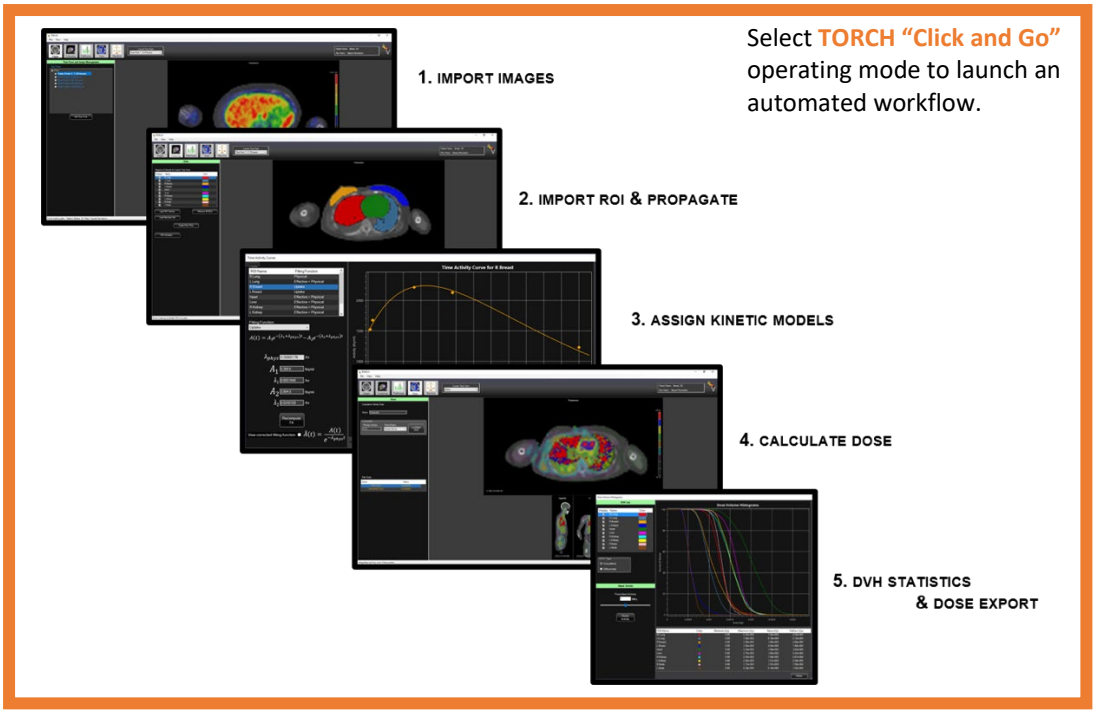

Figure 1. Simple five step workflow used in TORCH.

[1] TORCH has not yet been submitted to FDA for review of its Indications for Use and is therefore not suitable for clinical use.

TORCH consists of a dosimetry workflow which enables busy and resource limited clinics to complete personalized and accurate RPT dosimetry in five general steps (**Figure 1**). It can be operated either in an automated “Click and Go” fashion where the complete workflow is executed automatically or in an “Advanced” mode where the user interacts at each step manually. The first step is DICOM import where the user imports a CT and PET or SPECT dataset for each timepoint that the patient was imaged. Currently, TORCH does not perform SPECT calibration, so the user must input a calibration factor (i.e., cps/MBq) when importing SPECT data that is calculated using another software. It is recommended that the calibration factor is measured onsite by imaging a uniform phantom with the same imaging parameters as the patient data.

Next, the user imports either DICOM structure sets or ROI index files for at least one imaging time point. For multiple timepoint dosimetry, the user is required to import a set of ROIs for the first timepoint from an external image processing software. For subsequent timepoints, TORCH will propagate the contours across timepoints using proprietary GPU-accelerated deformable registration algorithms. The user can also choose to import their own ROIs for these additional timepoints.

To calculate cumulative activity for an ROI (or voxel), TORCH provides modeling tools to characterize the behavior of the radiopharmaceutical outside of the measured time points (i.e., interpolation and/or extrapolation). Given the ROI time activity curve data, TORCH utilizes the Akaike information criterion (AIC) to find the function which best fits the curve and provides the fitting parameters which were determined. The user can accept TORCH results or can choose from other fitting functions within the library or can manually adjust the parameters of the selected function. TORCH supports various types of kinetic models that exhibit various forms of uptake and multi-phasic clearance. Users that prefer numerical methods can choose to apply trapezoidal integration followed by physical decay after the final time point.

Next, radioactive decays in each activity rich voxel are sampled, and radiation is transported throughout the entire patient volume using TORCH MC radiation transport algorithm, which is a modified version of the MC dose calculation code Dose Planning Method (DPM)[1] that has been optimized to operate on GPUs. The MC algorithm uses an accurate and efficient coupled electron-photon transport scheme that retains many of the performance gain enhancements of the original DPM code. Electron transport is done using the condensed history method where large energy transfers are accounted for in the analogue sense and small energy transfers are accounted for by the continuous slowing down approximation. By analogue, it is meant that particles are transported on an event-by-event basis with no dependencies on variance reduction techniques or physics input other than physical cross sections. After each step, the angular distribution of electrons is determined using a step size independent multiple scattering theory. Photons are transported using a standard analogue approach accounting for photoelectric absorption, Compton scattering, and when applicable, pair production. Improvements in photon transport performance are achieved by implementing the δ-scattering method. Radioactive decay is handled using a per-decay sampling approach with source biasing.

Lastly, the radiation transport distribution is evaluated using dose volume histograms (DHVs) or ROI dose statistics. Here, a dosimetry report can be generated which is structured to meet the

requirements for “Complex Dosimetry” billing codes in the U.S. In addition, RT Dose volumes can be exported in either DICOM-RT or raw format to be visualized in another software package, e.g., possible combination with external beam radiotherapy.

TORCH has been thoroughly benchmarked and validated using both computational and physical phantoms. It’s dose calculations have been benchmarked against the general-purpose Monte Carlo code Geant4[2], which is a versatile object-oriented simulation toolkit that allows for the modeling of complex geometries, radiation sources, and detectors, has been used for a variety of different medical physics applications including RPT dosimetry[3–8]. Voxel S-kernels for multiple RPT isotopes in water have been calculated in TORCH and compared to Geant4 (data not shown). In addition, TORCH has also been benchmarked using data provided by the OpenDose collaboration, which averages the results of three Monte Carlo codes: EGS++ 2018, GATE 8.1, and GEANT4 10.5 [9]. Reference S-values (as defined by the MIRD formulism) have been calculated in the ICRP adult male and female standard phantoms [10] for both monoenegetic sources and RPT isotopes. An example of this type of comparison is provided in **Figure 2**. A head-to-head comparison of the dose distributions calculated in TORCH and Geant4 was also performed using the ICRP phantom (**Figure 3**). For the TORCH simulations, 4.6917×10^7 total decays (1000 decays per source voxel) were simulated in 180 seconds for ^{131}I, 270 seconds for ^{90}Y and 100 seconds for ^{177}Lu on a NVIDIA GEForce RTX 2070 GPU card. **Figure 3C** shows the percent difference in absolute absorbed dose within an axial slice of the male ICRP phantom where the liver (i.e., source organ) contains ^{131}I.

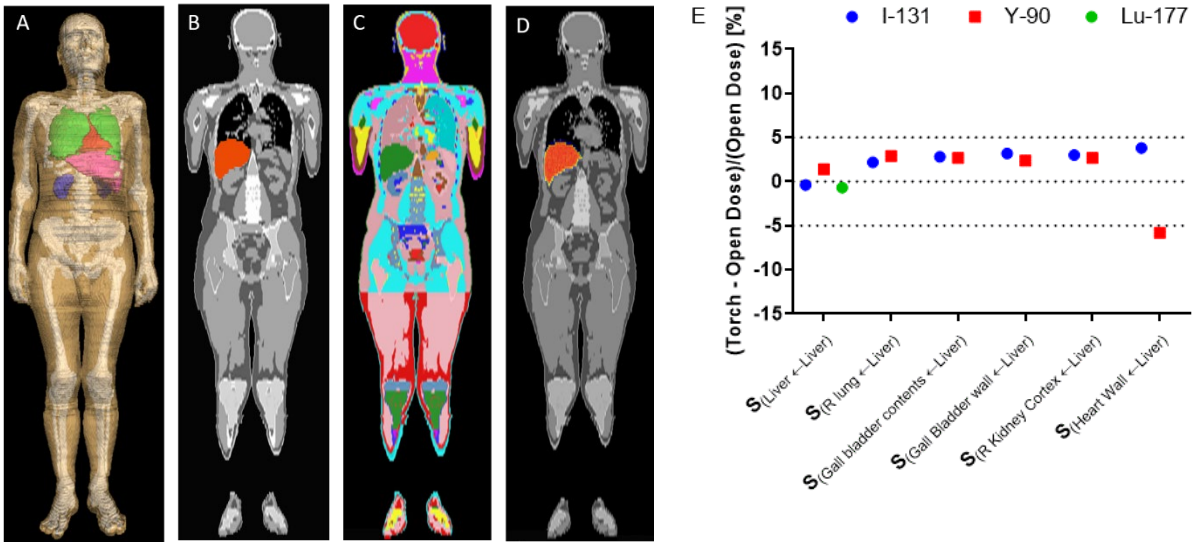

Figure 2. (A) Isosurface of Adult male ICRP phantom with organs of interest, (B) A synthetic nuclear medicine volume was created within the liver for each radioisotope (i.e., target), (C) Regions of interest were created based on the identification numbers (ID) from the ICRP Publication 110, (D) A dose map was generated in TORCH, (E) S-value comparison between TORCH and Open Dose with respect to target and source organs. S-values for Lu-177 to adjacent organs are ~100x less than the S(liver←liver) and are therefore not shown.

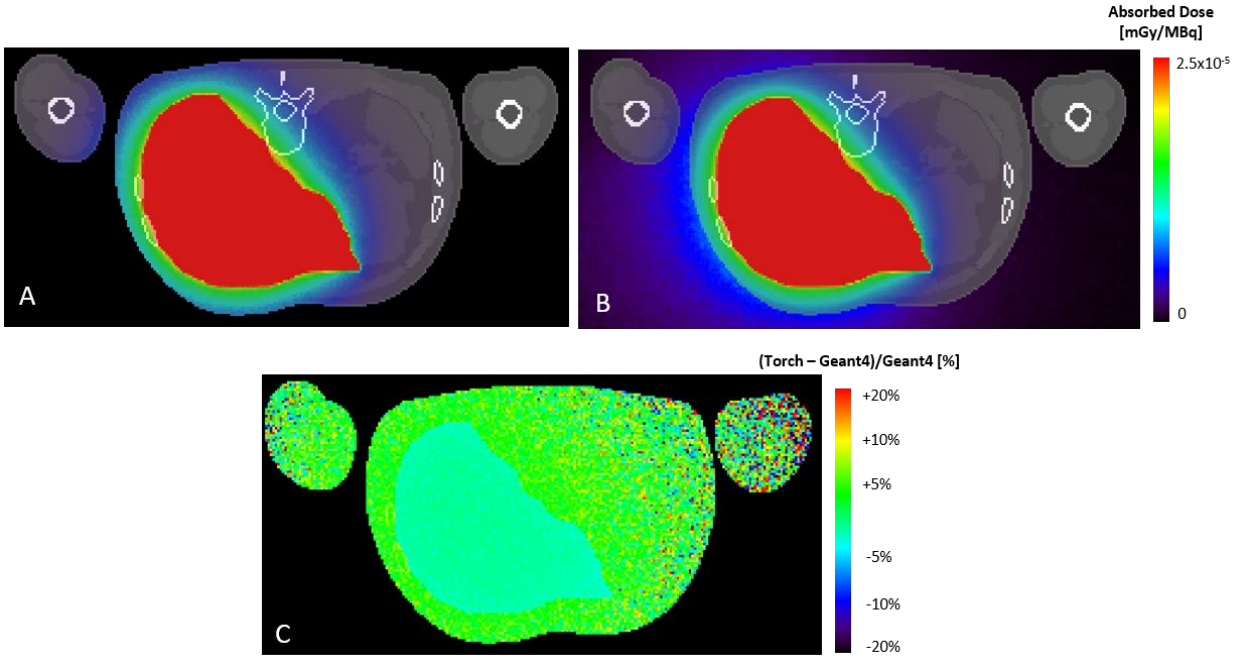

Figure 3. Axial slice of the absorbed dose distribution in the ICRP adult male phantom from a uniform activity of ^{131}I in the liver. calculated using (A) TORCH and (B) Geant4. Absorbed dose distribution are provided. As expected, most of the deposited dose is within the liver; however, in contrast to dose kernels, there is significant dose in the lungs and chest cavity as well. (C.) Percent difference color wash between TORCH and Geant4. Note, the regions or larger percent differences are significantly impacted by statistical uncertainties associated with both simulations.

Voximetry has partnered with the University of Wisconsin Accredited Dosimetry Calibration Laboratory (ADCL) to design and acquire physical measurements that demonstrate the accuracy of TORCH. A custom-made film phantom was developed in collaboration UW ADCL to benchmark the electron transport in TORCH MC. The film phantom (see **Figure 4**) consisted of a film stack (alternating active layer (top) and protective layer (bottom)), separated with thin slabs of solid water in the case of ^{90}Y exposures. Above the film stack was a cylindrical shell of PMMA that houses the radioactive solution. This solution was separated from the film stack by a very thin Kapton layer (7.62 µm). The film was calibrated using a 250 kVp NIST traceable x-ray beam. Liquid solutions of ^{90}Y and ^{131}I were injected into the phantoms for continuous exposures. Activities and exposure times were adjusted to deliver approximately 350 cGy to the first film layer. Excellent agreement is achieved for between TORCH and measured depth-dose distributions (e.g., ^{90}Y comparison shown in **Figure 4D-E**).

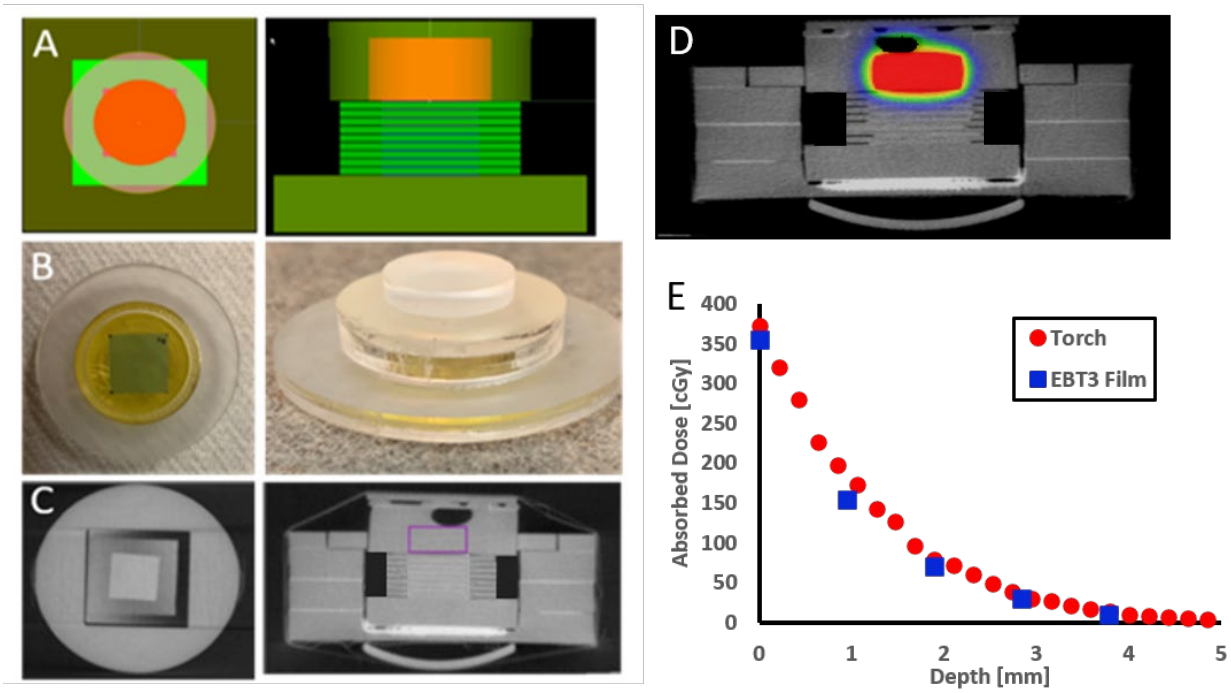

Figure 4: Phantom (A) Film phantom in EGS, (B) Physical phantom design, (C) CT scan of film phantom, (D) Dose distribution of the phantom in TORCH, and (E) depth dose results comparing film, EGS, and TORCH for ^{90}Y.

TORCH will be the first commercial coupled electron-photon Monte Carlo algorithm for RPT dosimetry. It leverages the enormous computing power of graphics processing units (GPUs) to calculate absorbed dose distributions at the voxel level. TORCH automated workflows will make RPT treatment planning faster and more accurate, so that it can be used clinically to complete complicated patient-specific dosimetry tasks within minutes thereby decreasing the time and staffing needs typically required to compete these procedures.

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For more information on TORCH, or other Voximetry technologies, please reach out to us at:
www.voximetry.com