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A medical image-based graphical platform—Features, applications and relevance for brachytherapy

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ABSTRACT

PURPOSE: Brachytherapy dose calculation is commonly performed using the Task Group-No 43 Report-Updated protocol (TG-43U1) formalism. Recently, a more accurate approach has been proposed that can handle tissue composition, tissue density, body shape, applicator geometry, and dose reporting either in media or water. Some model-based dose calculation algorithms are based on Monte Carlo (MC) simulations. This work presents a software platform capable of processing medical images and treatment plans, and preparing the required input data for MC simulations.

METHODS AND MATERIALS: The A Medical Image-based Graphical platfOrm—Brachytherapy module (AMIGOBrachy) is a user interface, coupled to the MCNP6 MC code, for absorbed dose calculations. The AMIGOBrachy was first validated in water for a high-dose-rate ^{192}Ir source. Next, dose distributions were validated in uniform phantoms consisting of different materials. Finally, dose distributions were obtained in patient geometries. Results were compared against a treatment planning system including a linear Boltzmann transport equation (LBTE) solver capable of handling nonwater heterogeneities.

RESULTS: The TG-43U1 source parameters are in good agreement with literature with more than 90% of anisotropy values within 1%. No significant dependence on the tissue composition was observed comparing MC results against an LBTE solver. Clinical cases showed differences up to 25%, when comparing MC results against TG-43U1. About 92% of the voxels exhibited dose differences lower than 2% when comparing MC results against an LBTE solver.

CONCLUSION: The AMIGOBrachy can improve the accuracy of the TG-43U1 dose calculation by using a more accurate MC dose calculation algorithm. The AMIGOBrachy can be incorporated in clinical practice via a user-friendly graphical interface.

Keywords: Brachytherapy; Monte Carlo; Model-based dose calculation algorithms; User interface

Introduction

Brachytherapy treatments are commonly performed using the Task Group-No 43 Report-Updated protocol (TG-43U1) (1, 2) absorbed dose to water formalism, which neglects human tissue densities, material compositions, body interfaces, body shape, and dose perturbations from applicators. These effects can be significant (3, 4) in the brachytherapy photon energy range and can be included

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in modern treatment planning systems (TPS) for brachytherapy by using model-based dose calculation algorithms. This new approach is needed to replace the TG-43U1 absorbed dose to water formalism with a more accurate dose estimation procedure. The American Association of Physicists in Medicine TG-186 (5) recently issued guidelines toward implementing TPS, which can take the above-mentioned complexities into account.

Some model-based dose calculation algorithms use Monte Carlo (MC) simulation codes, which offer a high accuracy for dose calculations. However, most MC codes lack a user-friendly interface to process the input and output data of brachytherapy dose calculations. This may involve several medical images, imaging artefact corrections, up to hundreds of dwell positions, and source and applicator geometries.

A Medical Image-based Graphical platfOrm—Brachytherapy module (AMIGOBrachy) is a software module developed to create an efficient and powerful user-friendly graphical interface, needed to integrate clinical treatment plans with MC simulations. It does this by providing the main resources required to process and edit images, import and edit treatment plans, set MC simulation parameters, run MC simulations, and analyze the results. In the current implementation, the MCNP6 (Monte Carlo N-Particle) (6) MC code is used for the simulations. This work describes AMIGOBrachy's design, main functionalities, and the validation process. Two clinical cases are shown; one intracavitary gynecologic case and one interstitial arm sarcoma case, both treated with an ^{192}Ir source.

Methods and materials

MC code

The MCNP6 is a multipurpose radiation MC transport code widely used in medical physics. The MC simulations using high-resolution voxel phantoms must handle a large amount of data requiring a large RAM memory and long CPU times. To increase simulation efficiency, the Harvard/Massachusetts Institute of Technology Boron Neutron Capture Therapy clinical trials team developed lattice speed tally enhancement (LSTE) for simulations with large number of voxels (7).

The LSTE function can be used under specific situations such as: (*1*) a hexagonal lattice must be present in the geometry, (*2*) all F4 tallies contain a hexahedral lattice, (*3*) all F4 tallies have associated DE/DF cards, and (*4*) nested lattices are scored together. However, this function is not compatible with all tallies. Simulations with F4 tallies can be faster by a factor of 100 or more than simulations with F6 tallies because LSTE does not work for F6 tallies, although both tallies are track length–based estimators. When the SPDTL card is active, tracking is more efficient because it considers only lattice geometries enclosed in a parallelepiped, removes general surface checks, removes extraneous energy bins, and tally modifiers. The LSTE retains only the tally multipliers (DE/DF cards) necessary to convert average photon energy fluence to kerma (7).

The MCNP6 calculations were performed using a track length estimator tally, FMESH, converted to kerma using mass–energy absorption coefficients from *National Institute of Standards and Technology* (8). All cases were simulated using the ^{192}Ir photon spectrum available from the National Nuclear Data Center (9). Photons were transported down to an energy cutoff of 1 keV, using the MCPLIB84 photon cross-section library without secondary electrons transport.

AMIGOBrachy

Figure 1 shows a diagram of the main functionalities of the software describing the entire process. AMIGOBrachy has been developed using MATLAB version 8.0 (Mathworks, Inc., Natick, MA) with the aim of providing tools

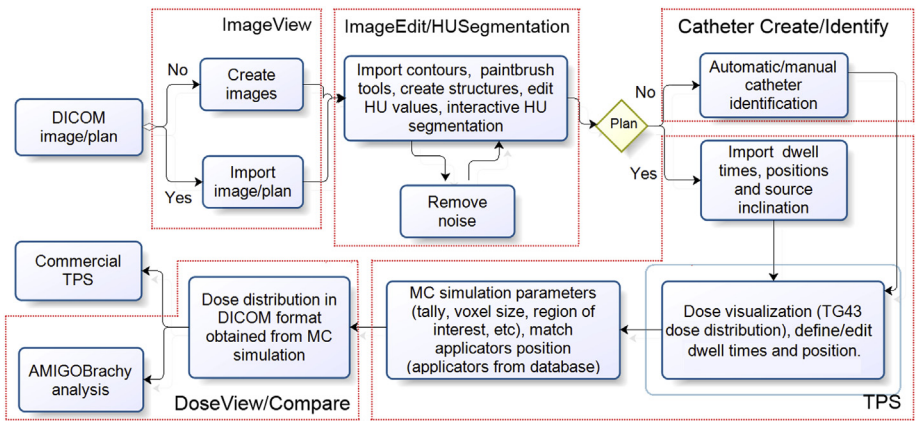

Fig. 1. Flowchart with AMIGOBrachy's main functionalities, which are described in the user-guide. The process starts with importing or creating a DICOM sequence of images, followed by defining the simulation parameters and initiating MCNP6, and finishes by importing and analyzing the simulated dose distributions. DICOM = Digital Imaging and Communications in Medicine; AMIGOBrachy = A Medical Image-based Graphical platfOrm—Brachytherapy module; MCNP6 = Monte Carlo N-Particle; HU = Hounsfield unit; TPS = treatment planning systems; TG-43 = Task Group Report No. 43; MC = Monte Carlo.

such as: (*1*) medical image processing, (*2*) dwell position identification, (*3*) needle detection, (*4*) phantom creation using Digital Imaging and Communications in Medicine (DICOM) images, (5) MCNP6 code input file creation, and (*6*) dose analyses. All functionality of AMIGOBrachy is achieved through a user-friendly interface. The software is compatible with the TPS Oncentra (Nucletron, an Elekta company, Stockholm, Sweden) and BrachyVision (Varian Medical Systems, Inc., Palo Alto, CA) offering the capability to import treatment plans created on both TPS and perform simulations using the MCNP6 code. Currently, CT and MRI images can be imported, but automatic segmentation and density calibration curves are not available for MRI images, which should be segmented using contours or thresholds defined by the user.

The software creates a MCNP6 input file by initiating several simulation parameters, for example, the energy cutoff, detailed or simple physics, the selection of tallies, and regions of interest. In addition, one can choose between the following transport/scoring schemes: photon transport in water and dose scoring in water ($D_{w,w}$), photon transport in the medium and dose scoring in water ($D_{m,w}$), or photon transport in the medium and dose scoring in the medium ($D_{m,m}$) (5). The AMIGOBrachy can be readily adapted to prepare MC input files for other MC codes. Although simulations are performed with MCNP6, the user has no need to interact with the code because AMIGOBrachy starts the simulation and automatically imports the results.

The MCNP6 can generate photon energy distributions in all voxels, which can be used for energy response correction of radiation detectors (10). This also allows studying the effect of nonwater heterogeneities on the photon spectrum. This capability was built into the current implementation of AMIGOBrachy.

The AMIGOBrachy can import the trajectory of the source and simulate the source movement using source speed profiles defined by the user. A previous study (11) discussed the methodology to derive the transit dose component for brachytherapy treatments.

Brachytherapy applicators

Commercial or in-house made brachytherapy applicators have a wide range of geometries and compositions. Some applicators may impact the dose distribution significantly owing to the geometry and the material used. The AMIGOBrachy can handle applicators in three different ways:

1. Using a database of applicators defined through an analytical geometry (Fig. 2a) combined with voxel phantoms. In this first version, two plastic applicators and one metal needle are available.
2. Converting applicator contours to voxels (Fig. 2b).
3. Using mesh geometries (MGs; Fig. 2c) created by computer-aided design and computer-aided engineering to perform simulations using MCNP6 (12).

The applicator's position can be obtained from DICOM file headers, when available, or defined by the user through two or more points depending on the applicator geometry. Moreover, applicators can consist of one or more small and/or thin structures, which cannot be accurately represented by regular voxels (i.e., the hollow needle in Fig. 2b).

The MCNP6 uses a finite element method to handle MGs created using first- and second-order tetrahedral, pentahedral, and hexahedral elements. The MG can be created with programs such as ABAQUS (Dessault Systèmes, Vélizy-Villacoublay, France) or ATTILA (Transpire, Inc., Gig Harbor, WA), which are fully compatible with MCNP6 (12).

Validation

Dose distributions obtained with AMIGOBrachy/MCNP6 were compared against dose distributions exported from BrachyVision version 10.0 using a linear Boltzmann transport equation solver, ACUROS (Transpire, Inc.), which can handle nonwater heterogeneities (13–17).

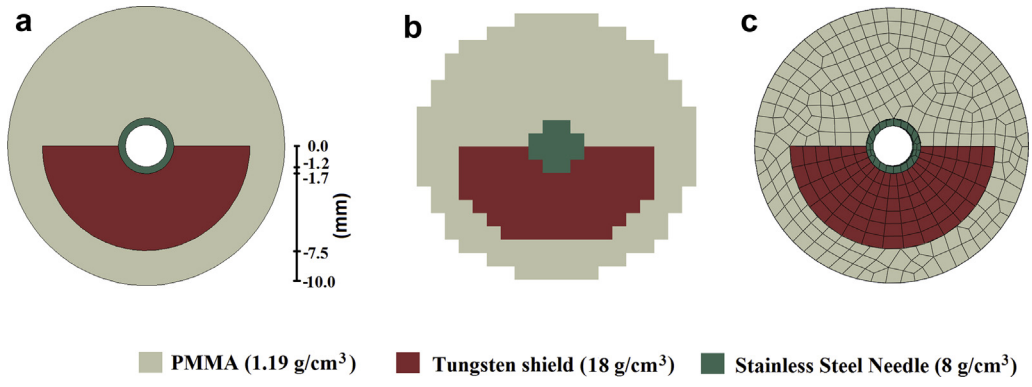

Fig. 2. A 180° tungsten-shielded applicator modelled using: (a) analytical geometry, (b) $1 \times 1 \times 1$ mm^3 voxels, and (c) mesh structures created with ABAQUS (Dessault Systèmes, France). The dimensions are based on the GM11004380 applicator (Varian Medical Systems, Inc., Palo Alto, CA) and on the ACUROS (Transpire, Inc., Gig Harbor, WA) applicator database (19). PMMA = polymethyl methacrylate.

Uniform phantoms

The validation process involved several steps going from source parameter validation up to clinical case comparisons against a commercial TPS. The AMIGOBrachy currently models two HDR ^{192}Ir sources, namely microSelectron (Nucletron) (18) and Gammamed Plus (Varian Medical Systems) (19), and an electronic brachytherapy X-ray source (Axxent; Xoft, San Jose, CA) (20). The Gammamed source was validated by comparing TG-43U1 parameters such as anisotropy function, radial function, and air kerma strength against values from the literature. Dwell times and dwell positions were validated by comparing the MC input generated with AMIGOBrachy against DICOM header information and reports from TPS.

Material compositions and dose grid effects were verified by comparing dose distributions obtained with a DICOM object of $200 \times 200 \times 200$ voxels, with a 1 mm resolution, consisting of a cubic phantom ($10 \times 10 \times 10$ cm^3) positioned in the middle of the image and surrounded by air, created for validation purposes. Simulations were performed for nine dwell positions within homogeneous phantoms consisting of all tissues available in the ACUROS library (lung, adipose tissue, water, muscle, cartilage, and bone) (21) using dose scoring grids of 1 mm slice thickness and a width/height of 0.50, 1, 2.50, and 5.0 mm.

Clinical cases

Two treatment plans were created for a Gammamed Plus (Varian Medical Systems) ^{192}Ir source using DICOM patient images from one interstitial and one intracavitary case. The dose distributions were calculated considering the material compositions and densities provided in the ACUROS user guide. The dose grid resolution was the same as the image resolution used in each case, whereas the dose grid sizes (i.e., the number of voxels) were defined interactively considering the ACUROS memory requirements.

The treatment plans were then imported in AMIGOBrachy to generate MCNP6 input files by reproducing the TPS configuration. This includes tissue contours, materials, dwell positions, applicator, dose grid, and voxel size. Dose calculations were reported as $D_{w,w}$ (as adopted by TG-43U1) and $D_{w,m}$, with the type A ($k = 1$) simulation uncertainty component less than 1% within the region covered by the 30% isodose.

Figure 3 presents a sequence of images illustrating the steps necessary to perform a simulation using a treatment plan imported by AMIGOBrachy.

Intracavitary case

The treatment plan for an intracavitary gynecologic case was made with a DICOM CT image set consisting of 63 slices with 512×512 voxels, 3 mm slice thickness, and voxel size of 0.98 mm. Dose distributions were calculated for a single guidance needle in the middle of a hollow plastic cylinder applicator (external diameter of 3.5 cm and 0.4 cm wall thickness). The applicator is placed in a phantom representing the patient with all voxels assigned to one of the six materials (polyphenylsulfone [modelling the applicator], water, bone, muscle, adipose tissue, and air) from the ACUROS database. There are 17 dwell positions and the prescribed dose is 7.5 Gy per fraction at 0.5 cm from the applicator's outer wall. The following situations were considered: (*1*) "infinite" homogeneous water phantom with at least 20 cm of water between the scoring voxels and the closest boundary with air (22); (*2*) body boundaries defined using CT images with all materials assigned as water, including the applicator; (*3*) CT-based geometry where tissues are assigned as water and the applicator assigned with its real composition; and (*4*) CT-based geometry with tissues and applicator assigned with their proper composition. Air was assigned to the regions outside the body except for Case 1.

Interstitial case

The treatment plan for an interstitial arm sarcoma case was made with a DICOM CT image set consisting of 253 slices with 512×512 voxels, 1.25 mm slice thickness, and voxel size of 0.59 mm. Dose distributions were calculated considering nine channels, 106 dwell positions, and a

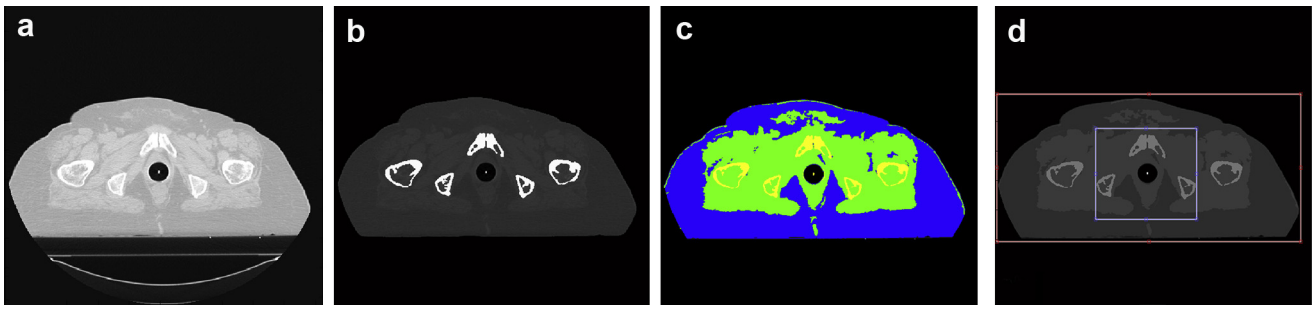

Fig. 3. A sequence of images used by A Medical Image-based Graphical platfOrm—Brachytherapy module: (a) importing the digital imaging and communications in medicine (DICOM) patient CT image; (b) defining structures by importing DICOM contours (e.g., the highlighted bone contours); (c) defining the material map (using Hounsfield unit numbers or drawing tools), which consists of air (black region), adipose tissue (blue region), muscle (green region), and bone (yellow region) and; (d) defining the voxel phantom region (external rectangle) and the dose scoring region (internal rectangle). (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

total dwell time of 336.6 s. The following situations were considered: (*1*) "infinite" homogeneous water phantom, as defined in the previous validation case, (*2*) all tissues assigned as water, (*3*) all tissues assigned as muscle, and (*4*) tissues assigned as muscle and bone.

Plastic catheters were not modelled and air was assigned to the regions outside the body except for Case 1.

Results and Discussion

The AMIGOBrachy uses a user-friendly user interface, obviating any technical MCNP6 knowledge, thus considerably reducing the time necessary to process the treatment data and to perform an MC simulation. Figure 4 presents a few screenshots of AMIGOBrachy with the ImageView module, three-dimensional images, and dose distributions. As an example, a patient CT slice, a rendered organ, and a few dose distributions are shown.

Uniform phantoms validation

Dwell positions in AMIGOBrachy showed no differences from TPS values, indicating that AMIGOBrachy correctly imports the values from the TPS. Errors in the dwell positions were manually introduced, which led to clearly visible differences in the dose ratios even for positioning differences lower than 0.5 mm. Therefore, source mispositioning problems can be easily detected. Calculated TG-43U1 parameters (1, 2) for the source are in good agreement with literature parameters with most of the points showing less than a 1% dose difference. For GammaMed Plus, more than 90% and 99% of the anisotropy function values show agreement with Taylor and Rogers (19) within 1% and 2%, respectively.

Results for the water cube phantom with AMIGOBrachy/MCNP6 and ACUROS are in good agreement for all dose scoring grids. However, the agreement is affected by the scoring grid resolution because 95% of the voxel doses agree within 0.6%, 1.0%, 2.2%, and 3.2% for scoring grid widths and heights of 5.0, 2.5, 1.0, and 0.5 mm. Uncertainty values are larger for smaller water voxel sizes because all simulations were performed with the same number of primary photons. In addition, ACUROS solves the Boltzmann transport equation by discretizing its six variables (14–16) leading to some discretization artefacts that become visible with higher dose grid resolution. The mean

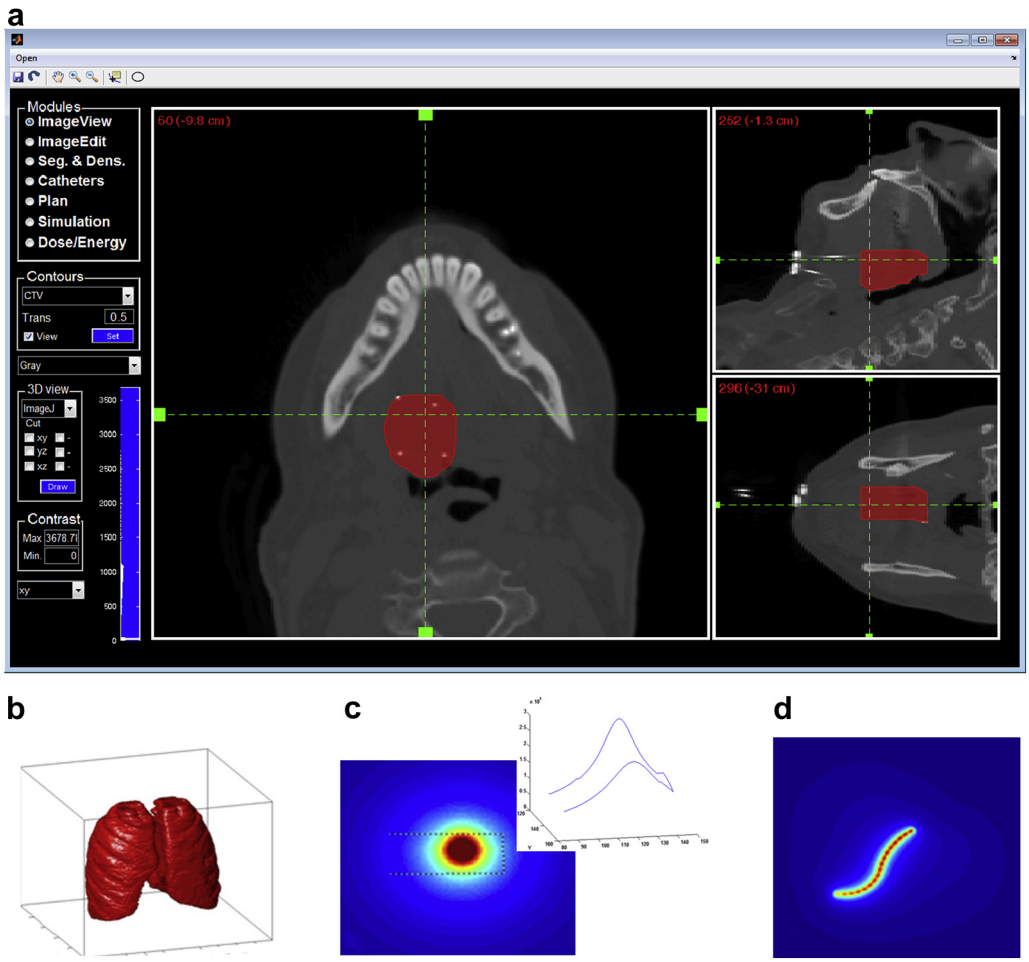

Fig. 4. A Medical Image-based Graphical platfOrm—Brachytherapy module (AMIGOBrachy) screenshots of (a) AMIGOBrachy ImageView module, (b) three-dimensional rendering of lungs, (c) dose distribution of a single source dwell position with dose profiles, and (d) dose distribution obtained using a titanium fletcher applicator and a sequence of source dwell positions.

dose per slice, obtained for statist reasons, for the evaluated grid sizes were compared against the 1 mm^3 grid. Differences lower than ±0.2% were observed for all.

Results obtained with phantoms of different materials were also compared using the mean dose per slice. The agreement between AMIGOBrachy/MCNP6 and ACUROS is the same for all tissues with mean differences per slice within ±0.3% when compared against values obtained with a water phantom. The ratio of the mean dose per slice (data not shown) was visually evaluated and no systematic differences were found.

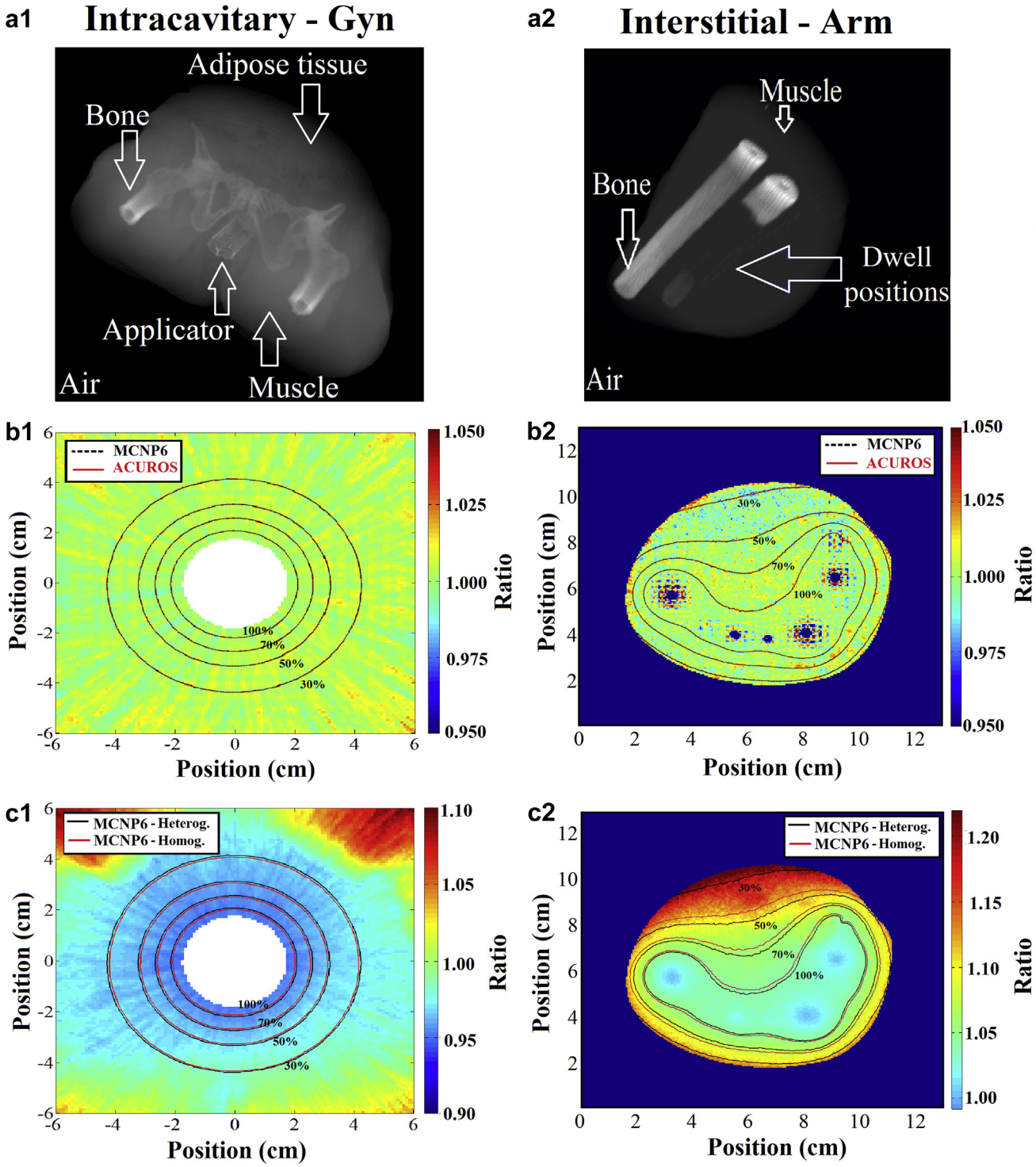

Fig. 5. Results for the two patient geometries: the intracavitary gynecologic case (1) and the interstitial arm case (2). (a) Three-dimensional view indicating the assigned materials, (b) isodoses and dose ratio ACUROS/MCNP6, and (c) isodoses and dose ratio MCNP6 (homogeneous water)/MCNP6 (heterogeneous geometry). MCNP6 = Monte Carlo N-Particle.

Clinical cases validation

The results obtained with AMIGOBrachy/MCNP6 for both patient cases were in good agreement with the values calculated with ACUROS, with differences of less than 2% and 5% for more than 92% and 98% of voxels with doses higher than 10% of the prescribed dose, respectively. Larger differences were observed in regions with a dose below 10% of the prescribed dose, which were owing to the statistical uncertainty of the simulation. Figure 5 shows the results obtained including a three-dimensional CT view (top), the dose ratio between ACUROS and MCNP6 (middle), and the dose ratio of MCNP6 for a homogeneous water medium and the proper material compositions (bottom).

The agreement between MCNP6 calculations for the intracavitary case performed using an applicator defined analytically and ACUROS is slightly lower than the agreement obtained using voxels for both codes with 87% of the voxels with differences less than 2%. This is owing to the differences in the gynecologic applicator position and the model because the analytical model of the applicator (MC) was compared against a voxel model. It was not possible to include the applicator in the ACUROS applicator database leading to different models, similar to the illustration in Fig. 2 for another applicator.

The intracavitary case shows isodose displacements of about 1 mm and dose differences of around 5% in the region within the 100% isodose, which is mostly owing to the hollow applicator effect because no significant difference was observed in the simulations modelling water or the actual tissue composition. The effect of the soft tissue composition and density is less than 1% for soft tissue, with no significant isodose displacement. The effect of the finite body dimensions is also visible in Fig. 5c1 showing increasing differences toward the boundaries of the body. This represents a lower dose obtained with MCNP6 because the air around the body reduces the number of backscattered photons, which is neglected by the TG-43U1 formalism.

The interstitial case also shows significant dose differences when MCNP6 is used with tissue heterogeneities and uniform water. Isodose displacements were obtained up to 1.6 and 4.1 mm for the 100% and 50% isodoses, respectively. Inside the 100% isodose, the underdose using proper tissue composition is about 5% with differences increasing toward the outer surface of the arm. The effect of the soft tissue composition and density is less than 1%. The bone medium yields displacements of up to 0.4 cm in the 100% isodose at some points behind this material.

Clinical applicability

The simulation efficiency depends on the clinical case with potentially significant differences because the effects of LSTE and geometrical optimization can depend on the case and on the user-defined parameters. The size of the region that is voxelized (Fig. 3d) also influences both efficiency and accuracy.

Simulations using the track length estimator tally (MCNP6 F6) with the LSTE function disabled required at least 100 times longer calculation times than those performed using FMESH (virtual grid-based track length estimator tally) with the LSTE function activated. This result agreed with the LSTE description and was performed only for one case to estimate the simulation time (7). Simulation time for the gynecologic case can also be reduced by up to 24% and the RAM memory requirements almost 100 times by defining the voxel phantom and the dose grid size. This can be done interactively with AMIGOBrachy or can simply be accepted from the treatment plan.

The feasibility of clinical implementation was evaluated by simulating the intracavitary case with 6.6×10^6 voxels assigned to specific materials, a dose scoring grid of $100 \times 100 \times 20$ voxels and a dose grid resolution of $1 \times 1 \times 3$ mm^3. The simulation time necessary to obtain an average dose uncertainty of 2% inside of the 50% isodose region for 5×10^7 particles, using an Intel i7 (2860QM) processor with four cores of 2.5 GHz and 8 GB of RAM memory, is 69 min. On a more powerful Intel Xeon X5650 processor with 12 cores of 2.67 GHz and 32 GB of RAM the simulation time is 27 min, and this reduces to 5 min on an SGI C2112 server (Silicon Graphics International Corporation, Chippewa Falls, WI) consisting of 16 processors with eight cores of 2.4 GHz each.

The MC dose calculation should initially be used to evaluate the differences with TG-43U1 treatment plans, providing valuable information regarding heterogeneity corrections. Besides dose evaluation AMIGOBrachy/MCNP6 can be used to calculate the mean photon energy in voxels, which can be useful for energy-dependent dosimeter corrections or for studies on relative biological effectiveness (23).

Conclusion

The AMIGOBrachy offers a user-friendly interface providing resources to perform clinical brachytherapy dose calculations based on MC simulation. It takes into account the body geometry, tissue composition, and applicator attenuation as recommended by TG-186. The studied cases show good agreement with ACUROS with some under- and overdosing compared with TG-43U1–based dose with differences of around 5% within the target volume and up to 25% within the evaluated regions. The AMIGOBrachy can improve the accuracy of the dose distribution through a more accurate applicator representation and/or a more accurate dose calculation algorithm. Moreover, the AMIGOBrachy can import applicators in the computer-aided design format and includes metal needles that are not present in the ACUROS applicator database.

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