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AAPM WGDCAB Report 372: A joint AAPM, ESTRO, ABG, and ABS report on commissioning of model-based dose calculation algorithms in brachytherapy

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Abstract

The introduction of model-based dose calculation algorithms (MBDCAs) in brachytherapy provides an opportunity for a more accurate dose calculation and opens the possibility for novel, innovative treatment modalities. The joint AAPM, ESTRO, and ABG Task Group 186 (TG-186) report provided guidance to early adopters. However, the commissioning aspect of these algorithms was described only in general terms with no quantitative goals. This report, from the

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Working Group on Model-Based Dose Calculation Algorithms in Brachytherapy, introduced a field-tested approach to MBDCA commissioning. It is based on a set of well-characterized test cases for which reference Monte Carlo (MC) and vendor-specific MBDCA dose distributions are available in a Digital Imaging and Communications in Medicine—Radiotherapy (DICOM-RT) format to the clinical users. The key elements of the TG-186 commissioning workflow are now described in detail, and quantitative goals are provided. This approach leverages the well-known Brachytherapy Source Registry jointly managed by the AAPM and the Imaging and Radiation Oncology Core (IROC) Houston Quality Assurance Center (with associated links at ESTRO) to provide open access to test cases as well as step-by-step user guides. While the current report is limited to the two most widely commercially available MBDCAs and only for ^{192}Ir-based afterloading brachytherapy at this time, this report establishes a general framework that can easily be extended to other brachytherapy MBDCAs and brachytherapy sources. The AAPM, ESTRO, ABG, and ABS recommend that clinical medical physicists implement the workflow presented in this report to validate both the basic and the advanced dose calculation features of their commercial MBDCAs. Recommendations are also given to vendors to integrate advanced analysis tools into their brachytherapy treatment planning system to facilitate extensive dose comparisons. The use of the test cases for research and educational purposes is further encouraged.

KEYWORDS
brachytherapy, commissioning, dose calculation, model-based dose calculation, Monte Carlo, TG-186

1 | INTRODUCTION

Introduction of model-based dose calculation algorithms (MBDCAs), capable of accounting for tissue and applicator heterogeneities in brachytherapy treatment planning, is an important development.[1] It enables further individualization of treatments, improved understanding of dose–response relationships and safer introduction of new sources, applicators, and techniques not possible using the simplistic "all-water" approach of the TG-43 formalism.[2]

The implications of using MBDCAs across the spectrum of brachytherapy procedures have been extensively examined, for example, TG-186 report and references therein.[3] Significant departures from the relevant TG-43 formalism exist for low energy brachytherapy (e.g., ^{103}Pd, ^{125}I, ^{131}Cs, or electronic brachytherapy), intermediate (e.g., ^{169}Yb) and high energy brachytherapy sources (e.g., ^{192}Ir and less so for ^{60}Co). Safer introduction of therapeutic approaches involving radionuclides and electronic brachytherapy sources with lower energy,[4–7] directional sources,[8] and new shielded applicators for dynamically modulated brachytherapy[9–13] all depend on the ability of dose calculation algorithms to correctly account for all of the treatment details (e.g., geometry and material compositions). In some instances, MBDCAs for high dose-rate (HDR) ^{192}Ir sources have been implemented in commercial treatment planning systems (TPSs) for several years and validated through independent studies.[14–22]

The process for commissioning the TG-43-based dose calculation aspect of the TPS is well-known.[2,23] Consensus datasets are available to the end-user,[2,24–26] having been generated by experts and vetted through formal processes established by professional and scientific societies.[27] It is the responsibility of the qualified medical physicist to ensure that the consensus data are properly utilized within the TPS.[2] The calculation geometry only considers source position(s) and the point of interest or, for an organ, the volume of interest. It is furthermore assumed to be an infinite water medium. Finally, the TPS dose calculation can be checked by manual calculation of the TG-43 formalism for this simple geometry: dose at specific points should be within 1% (exact agreement is expected at points coincident with tabulated data points).[23,28]

MBDCA validation via manual dose calculations is impossible. MBDCAs require not only the geometric details such as source positions and volumes, but also the density and elemental composition of each voxel comprising the patient geometry including the applicator(s) and, in permanent implants, the sources themselves to account for interseed attenuation. Furthermore, each MBDCA has implementation-specific assumptions and parameter settings intended to represent an optimal trade-off between accuracy and

calculation time. These are mostly unknown to the end-user in the context of a commercial implementation.

The TG-186 working group (WG) recognized in its report that the most thorough approach to MBDCA commissioning is to validate various calculation scenarios against Monte Carlo (MC) simulation and/or experiments.[14–18] For the former, this essentially translates into the end-users having to perform an extensive benchmarking of a "gold standard" MBDCA,[26] namely a MC code, in order to commission a commercial MBDCA implementation. For the latter, the end-user must address the challenges of the steep dose gradients, where a mm positional uncertainty can lead to tens of percent dose measurement error as well as additional challenges encountered by positional changes in energy spectrum and dose rate. Clearly, both the MC and the experimental approaches to commission a MBDCA TPS are beyond the capabilities of most end-users.

An alternative process to facilitate MBDCA commissioning has been proposed by Rivard et al.[29] where, similar to TG-43 consensus datasets, a number of calculation geometries associated with reference datasets (i.e., 3D dose distributions) would be available through the Brachytherapy Source Registry. This approach was made an integral part of the TG-186 report commissioning workflow (see for example Figure 4 of that report, reproduced herein as Figure 1).[3] With this in mind, the joint European Society for RadioTherapy and Oncology (ESTRO), Australasian Brachytherapy Group (ABG), American Brachytherapy Society (ABS), and American Association of Physicists in Medicine (AAPM) WG on dose calculation algorithms in brachytherapy (WGDCAB) were formed in 2011 with the following original charges:

1. Develop a limited number of well-defined test case plans and perform dose calculations and comparisons with MBDCAs.
2. Identify the best venue for hosting the reference plans/data and create a Registry in collaboration with identified partners.
3. Propose to the community well-defined prerequisites for test case plans to be submitted to the Registry.
4. Engage the vendors to promote uniformity of practice.
5. Develop a review process for the evaluation of new reference data meeting the prerequisites.

Over the last few years, the WGDCAB experts and vendors have come together to develop and integrate the necessary infrastructure to support importing and calculating a series of test cases across the different TPS versions and platforms.[30,31] Furthermore, working with the Imaging and Radiation Oncology Core (IROC) Houston Quality Assurance Center, the Brachytherapy Source Registry has been expanded to host reference datasets for these test cases. As such, significant progress with regards to Charges 1–4 has been achieved to lay a strong foundation for future work by WGDCAB, for example, the development of more clinically realistic test cases. Charge 5 has not been addressed yet and will be covered in a future report. Still, based on these extensive developments, over 250 medical physicists were able to participate in the process described in this report based on an open invitation at various annual meetings and at hands-on sessions of the 2017 AAPM Summer School,[32] and 2018 ESTRO Advanced Brachytherapy Physics Course.

The present report describes a practical implementation of the commissioning process outlined in the TG-186 report. It enables the end-users of either Varian's BrachyVision version of Acuros AcurosBV™ (Varian Medical System, Palo Alto, CA) or Elekta's TG186 ACE™ (Elekta Brachy, Veenendaal, The Netherlands) to fully perform both Level 1 and Level 2 TG-186 commissioning without running MC calculations or performing complex measurements themselves.[3] This report describes the available resources and infrastructure, guides the medical physicist through the commissioning workflow, presents recommended analysis approaches and tolerances, lists current limitations, and finally discusses the availability of Registry data for research and development purposes. In addition, the process described in this report also allows end users to explore the various benefits and limitations of a MBDCA TPS, thus providing an educational resource beyond commissioning.

The present approach to commissioning a MBDCA is the baseline recommended by AAPM, ESTRO, ABG, and ABS to brachytherapy end-users. It limits itself to commissioning and validation of commercially available MBDCAs for high-energy HDR ^{192}Ir brachytherapy applications. However, the infrastructure and workflow for commissioning described here could be extended to any brachytherapy MBDCA and to any photon energy range or dose rate.

2 | REVIEW OF AVAILABLE RESOURCES AND INFRASTRUCTURE

The AAPM, GEC-ESTRO,[33] and the IROC-Houston Quality Assurance Center have established a Brachytherapy Source Registry[34] (link: http://irochouston.mdanderson.org/rpc/BrachySeeds/Source_Registry.htm) to make available data used in the commissioning process. Specific to commissioning conventional TPSs that are based on the TG-43 dose calculation formalism, resources are available on the Registry and include:

- A policy outlining the procedure to recognize brachytherapy source models that meet the AAPM dosimetric prerequisites in regard to available dosimetry parameters and calibration traceability,

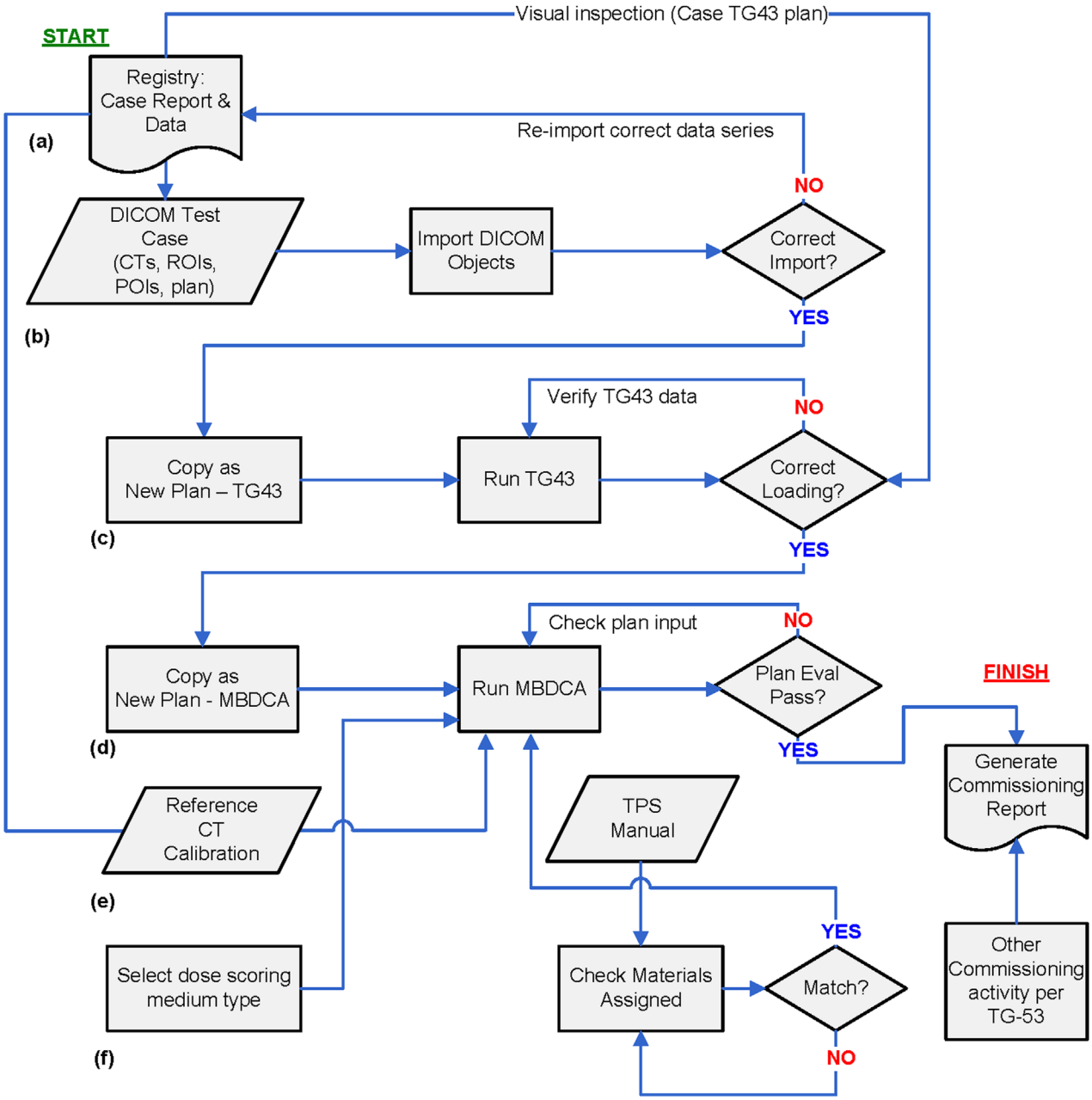

FIGURE 1 MBDCA Level 2 commissioning workflow. The main constituents (a) through (d) are described in the text, items (e) and (f) are from Beaulieu et al.,[3] with permission. MBDCA, model-based dose calculation algorithm.

- Source Model reference information—including Manufacturer contact information, a source design drawing, and relevant dosimetry references for specific source models,
- When available, societal reports presenting recommended dosimetry parameters.
- A web forum—to permit users to openly share their ideas and experiences.[35] Implemented by WGDCAB and the Brachytherapy Source Registry Working Group (WGBSR), this web forum has allowed users to identify opportunities for clarifying the instruction manuals and requirements for specific TPS software versions where commissioning processes may differ. As research and development grows on the topic, additional test cases could be added for different TPSs, radionuclides, and for de-identified, realistic, clinical patient examples.
- Commissioning-specific resources, including:
  - Test cases in the form of RT Image, RT Dose, RT Plan, and RT Structure Set DICOM-RT objects compiled in a separate ZIP file for each test case and vendor, prepared using the Elekta

Oncentra Brachy TPS (OcB—ACE v4.5) and the Varian BrachyVision TPS (AcurosBV versions 13 and 15, both in clinical use at time of publication),
- Corresponding reference data for RT Dose based on MC simulation results for each test case, and
- User Guides for the commissioning process, specific to each TPS, providing a step-by-step procedure on how to download and import reference data, make dose calculations with the end-user's TPS, compare these results, and certify that the user's TPS satisfies a given tolerance.

Specific to commissioning TPSs using MBDCAs, the Registry includes a generic HDR ^{192}Ir source prepared by the WGDCAB at the time of publication,[30] implemented by vendors of both currently available MBDCAs (Elekta's ACE and Varian's AcurosBV). A separate file is provided for importing the generic HDR ^{192}Ir source into the Elekta TPS. For Varian, depending on the TPS version (version 13 or higher), a source model for the generic WG source may have to be created before proceeding with test case import and dose calculations. Users should follow the BV reference guide instructions. The vendor-specific User Guides described below also contain information in this regard. Additionally, the Registry includes the following resources pertaining to four basic test cases for each vendor calculated with the generic source[30,31]:

- Test Case 1: source positioned centrally within a cube of water of 51.1 cm in length.[26]
- Purpose: provides a direct comparison of MBDCA TPS results with TG-43 dose calculation results for a single source position.
- Test Case 2: source positioned centrally within a 20.1-cm cube of water that is positioned within a 51.1 cm cube of air.
- Purpose: shows that the smaller water phantom produces negligible dose differences within 10 cm of the source compared to Test Case 1.
- Test Case 3: same as Test Case 2, except the source is offset 7 cm laterally and located 3.05 cm away from the water cube surface.
- Purpose: 3 evaluates the dosimetric influence of missing scattering material compared to a large phantom.
- Test Case 4: source positioned centrally within a generic tungsten-shielded vaginal applicator.
- Purpose: demonstrates the effects of shielding, especially obliquely near the source long axis.

Additional details on the preparation of these test cases and their use in both TPSs are described in Ballester et al. for Test Cases 1–3,[30] and in Ma et al. for Test Case 4.[31]

3 | MBDCA COMMISSIONING WORKFLOW

3.1 | Process constituents

The TG-186 report introduced two levels of commissioning.[3] Level 1 pertains to the verification of the algorithm in reference conditions for the dosimetric characterization of a source according to TG-43. Tolerances < 2% (in dose or dose rate) are expected at clinically relevant distances.[2,26] Level 2 pertains to the comparison of the end-user's MBDCA results with corresponding reference data in specific virtual phantoms mimicking clinical scenarios.

The dose distributions resulting from modeling the single source in a pure water phantom (Test Case 1) also serve to ensure the implementation of the correct source type in the TPS. Thus, once the MBDCA has been commissioned for the virtual source, the end-user should repeat Test Case 1 for the actual source type of their TPS and compare results with the system's TG-43 algorithm (previously validated with consensus datasets) to assure that their MBDCA can use the correct clinical source when intended.

Figure 1 reproduces the workflow diagram from the TG-186 report illustrating the elements and subprocesses involved in Level 2 MBDCA commissioning. The workflow for Level 1 commissioning is the same, albeit simpler in view of the homogeneous water geometry.

With reference to Figure 1, the main elements of a Level 2 commissioning workflow are:

a. The Registry described in Section 2 of this report serves as the source of treatment planning data and reference dose distributions for the test cases, prepared in Digital Imaging and Communications in Medicine—Radiotherapy (DICOM-RT) format. The required data can be downloaded from the Model-Based Dose Calculations database (link: https://doi.org/10.52519/00005).[36]
b. Download and import of treatment planning data for a test case including phantom geometry, precontoured structures, points of interest, material assignments, source strength(s), dwell positions, dwell times, the plan report, and other information contained in the DICOM-RT objects. Also, download and import of two reference dose distributions: MC and TPS (calculated by the WG).
c. Perform TG-43 dose calculations by the end-users for the test case and comparison with the Registry plan report to verify treatment plan parameters.
d. Perform MBDCA dose calculations by the end-users for the test case after steps (e), (f) in Figure 1; see Ref. 3 for details regarding these steps, and comparison with the Registry 3D reference dose distributions using TPS-based evaluation tools.

Level 2 commissioning involves comparing a dose distribution calculated locally by the TPS with a reference dose distribution downloaded from the Registry, for the same test case plan. It is essential that both distributions be obtained for the same value of the total reference air kerma (TRAK). As TRAK is proportional to source strength and total dwell time, preparing for the local dose calculation involves making sure that the source strength and dwell time are set to the values specified for each test case. By doing so, TRAK is assigned the same value as for the reference dose distribution, enabling direct comparison of the locally calculated and reference distributions.

3.2 | Detailed guidance

To facilitate the performance of the commissioning process for each test case in the Registry, User Guides providing detailed, step-by-step directions have been prepared. Separate guides are available for the commercially available TPSs that incorporate a MBDCA (currently Elekta OcB and Varian BV), reflecting their distinct user interfaces and accommodating variations in DICOM-RT implementations. Attention should also be given to the TPS version since, for example, users of BV TPS versions earlier than v13 will have to prepare the source model for the generic WG source[30] used in all test cases themselves, following the BV reference guide instructions.

3.3 | Testing and feedback

After implementation and testing the workflow shown in Figure 1 was completed for both the OcB and BV TPSs by WGDCAB members, a group of 17 experienced brachytherapy physicists external to the WG was recruited at the beginning of 2016 to perform further testing in the clinical setting. Feedback from this group confirmed the overall workability of the implementation, identified a number of technical and documentation inaccuracies that were subsequently corrected, and included suggestions for future improvements.

In a second step, the Registry was opened to public access at the World Congress of Brachytherapy in June 2016. In addition, hands-on MBDCA commissioning workshops were an integral part of the 2017 AAPM Summer School on Clinical Brachytherapy Physics as well as the 2018 ESTRO Advanced Brachytherapy Physics School, enabling hundreds of physicists having a broad range of brachytherapy experience to work with both the OcB and BV TPSs. Their collective ability to do so successfully and consistently, and their positive assessment of the commissioning process, provided further confirmation of the workability of the WGDCAB implementation.

Of the feedback received, two suggestions for improvement stand out as having the greatest potential to enhance the clinical utility of MBDCA commissioning.

- The first, set as a recommendation to TPS vendors, was to make the 3D dose distribution comparison tools used for external-beam radiotherapy (EBRT) planning available also for brachytherapy planning. Users expressed a strong need to have available the familiar assessment tools such as dose-difference histograms and gamma-index analysis methods in order to make well-informed decisions regarding the adequacy of commissioning tests and clinical treatment plans.
- The second suggestion was to formulate a specific, comprehensive MBDCA commissioning report format for each test case in the Registry. This would enable the direct comparison of commissioning results for users of a particular TPS and software version, and also facilitate such comparison between different TPSs and software versions. Such an approach is described in the next section.

4 | RECOMMENDED ANALYSIS AND TOLERANCES

There are several figures-of-merit that can be used to commission a MBDCA TPS. The procedure proposed in the following relies on the evaluation of dose differences and dose ratios between the dose distribution calculated by the user and the reference. For a detailed discussion on local and global dose ratios and their usage, the reader is referred to Ballester et al. and Ma et al.[30,31] The local dose difference ratio is:

$$\Delta D_{LOCAL} = \frac{D_{TPS,User}(x,y,z) - D_{ref}(x,y,z)}{D_{ref}(x,y,z)} \quad (1)$$

is defined as the difference between the dose obtained by the user using the TPS and a reference dose, based either on TPS or MC, at any point, normalized to the reference dose at the same location. Its purpose is to serve as an indicator of local dose discrepancies. For the purpose of this report, the x- and y-axes point along the source transverse plan while the z-axis points along the source long axis. The global dose difference ratio corresponds to the difference between the TPS dose and the reference dose at a given point normalized to a dose value at a clinically relevant reference point (1 cm away from the source center along the x direction for Test Cases 1–3 and 0.5 cm outside of the applicator for Test Case 4).

$$\Delta D_{GLOBAL} = \frac{D_{TPS,User}(x,y,z) - D_{ref}(x,y,z)}{D_{ref}(x_{ref},y_{ref},z_{ref})}. \quad (2)$$

The four test cases currently available to the community (see Section 2) were prepared to test MBDCA performance in various aspects of brachytherapy dosimetry. Test Case 1 corresponds to the highly benchmarked TG-43 single source data for the source type at hand and is thus a check that the correct source was implemented in the system. Test Cases 2–4 evaluate MBDCA performance in situations not accounted for by TG-43-based algorithms. While these test cases incorporate some of the simpler features of a clinical scenario, they do not actually comprise one. Hence, determining tolerance values based on clinical criteria is beyond the scope of the current report. However, to provide insight into the process, we describe here a commissioning tolerance making use of the ΔD_{LOCAL} figure of merit and the aforementioned four test cases.

With respect to the reference datasets, Ballester et al. and Ma et al. evaluated and discussed several different MC codes.[30,31] The user will need the corresponding commissioning dataset generated by the WG for each TPS for their particular software version. This dataset will be referred in the following as the TPS reference data, $D_{\text{TPS,ref}}$. Additionally, a dataset obtained using MCNP6 was selected as $D_{\text{MC,ref}}$ for the sake of consistency with the previous analyses,[30,31] and will be known henceforth as MC reference data. Using these datasets and the one calculated by the user, $D_{\text{TPS,User}}$, two ΔD_{LOCAL} volumetric distributions can be obtained:

$$\Delta D^{\text{TPS}}_{\text{LOCAL}} \text{ from } D_{\text{TPS,User}} \text{ and } D_{\text{TPS,ref}} \quad (3)$$

$$\Delta D^{\text{MC}}_{\text{LOCAL}} \text{ from } D_{\text{TPS,User}} \text{ and } D_{\text{MC,ref}} \quad (4)$$

The reference datasets for all test cases are stored at the Registry located in the Joint AAPM/IROC Houston Registry of Brachytherapy Sources webpage,[34] under the option *Model-Based Dose Calc menu*, as described in the previous section. Comprehensive step-by-step User Guides for implementing the test cases and undertaking preliminary checks are provided to the clinical user under the options *Elekta Database* and *Varian Database*.

The commissioning procedure proposed in the following is organized into two phases. Its workflow diagram is summarized in Figure 2.

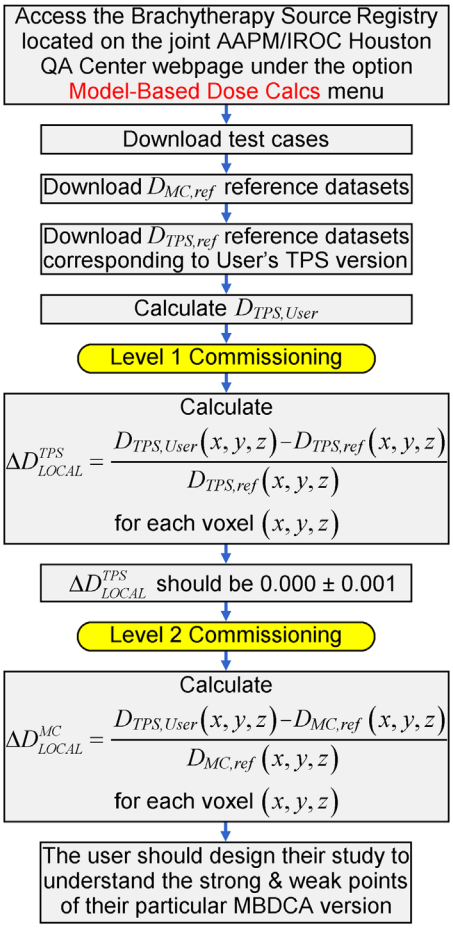

FIGURE 2 Commissioning analysis workflow diagram. The constituents are described in the main text.

4.1 | MBDCA preparation phase

The analysis recommended here depends critically on whether the user is applying the same TPS version as the one with which the TPS reference dataset was generated, or that the prior version was tested as valid for a newer version (see Section 5 for more details). Since currently available TPSs based on MBDCA are deterministic algorithms, $D_{\text{TPS,User}}$ and $\Delta D^{\text{TPS}}_{\text{LOCAL}}$ should agree for all voxels within the computer's numerical precision. Any deviation beyond some tolerance to account for rounding errors should be further investigated.

After $\Delta D^{\text{TPS}}_{\text{LOCAL}}$ is evaluated, the user is encouraged to make an initial comparison against a selected set of locations discussed in the User Guide document. If calculations at any of these locations exceed a 0.1% difference, $|\Delta D^{TPS}_{LOCAL}| \leq 0.001$, then steps must be taken to ensure that the User Guide procedures have been followed strictly.

Once this test has been passed, the user should evaluate the full volumetric distribution to ensure that no differences larger than 0.1% are found in any region.

4.2 | MBDCA validation phase

Providing that the *MBDCA Preparation Phase* checks have been successfully completed, the clinical user can be sure that the MBDCA TPS is properly set up and the dose reported corresponds to the one intended by the dosimetric plan. However, it is important that the clinical user realizes that both the Varian AcurosBV and Elekta

ACE TPS implementations of a MBDCA rely on different numerical approximations to evaluate collisional kerma, and, therefore, differences with respect to state-of-the-art MC simulations are to be expected at some locations.[17,18]

For the purpose of this report, expert-validated MC simulations are considered the *gold standard* in our description of the dose deposition, to which all other possible numerical techniques are to be compared against. MBDCA algorithms can be specifically tailored for clinical plans involving tens or even hundreds of dwell-positions in clinically relevant volumes; however, the single dwell-position cases discussed here are among the most challenging ones for both ACE and AcurosBV. Papagiannis et al.[17] analyzed the case of single-source and bounded homogeneous geometries for AcurosBV using the VariSource VS2000 source and for ACE using the mHDR-v2c source. In the case of AcurosBV, they reported differences in the range ±2% with respect to the TG-43 formalism for most parts of the volume. For ACE, although the observed discrepancies were also in the ±2% range up to 5 cm from the source, larger differences and ray-tracing discretization artifacts appeared from 5 to 15 cm from the source.[17,18] It is important to emphasize that, due to the large dose gradients existing in a single-source plan, the larger differences at distances further than 5 cm from the source might not be clinically relevant. Ballester et al. and Ma et al. designed and analyzed Test Cases 1–3 in detail for different 2D planes centered on the source.[30,31] Similar conclusions were found, reporting differences with respect to MC in the range ±1% for AcurosBV and −2% to +3% for ACE in clinically relevant regions. Ma et al. presented Test Case 4 and reanalyzed the full 3D volume of Test Cases 1–3 using the ΔD_{LOCAL} and ΔD_{GLOBAL} figures of merit.[30,31] The authors reported that the largest discrepancy was found for Test Case 4, which incorporated a shielded applicator. AcurosBV agreed with MC reference data within ΔD_{LOCAL} values of about ±4.2% for 95% of the voxels. This correlates with differences with respect to the dose at a clinically relevant reference point in the range ±0.12%. In the case of ACE, 95% of the voxels agreed with MC reference data, ΔD_{LOCAL} values, within −8% to +15%, resulting in dose differences within −1.7% to +0.4% of the clinically relevant dose.

With respect to more clinically relevant plans, there is a large body of knowledge in the literature evaluating the differences observed between MC simulations and MBDCA results at different clinical sites. It is beyond the scope of this report to perform a complete review of the field. The interested reader can find an extensive discussion on several clinical sites in Papagiannis et al.,[17] Sloboda et al.,[37] and references therein. Nevertheless, all MBDCA users are encouraged to perform a bibliographic study on the differences, and possible clinical consequences, expected between MBDCA, TG-43, and MC representing the best estimate of dose deposited at each clinical site of interest.

To explore possible differences, the user is expected to evaluate ΔD^{MC}_{LOCAL} for all voxels. With respect to Test Cases 1–4, the following steps should be undertaken to understand the benefits and limitations of a MBDCA TPS:

1. Comparison of $D_{\text{TPS,User}}$ values against $D_{\text{MC,ref}}$ values (cGy) for the same selected locations discussed in the *MBDCA Preparation Phase* commissioning procedure.
2. Analysis of the $\Delta D^{\text{MC}}_{\text{LOCAL}}$ 1D dose difference profiles along Cartesian coordinate lines passing through the center of the radiation source. This will imply analyzing $\Delta D^{MC}_{LOCAL}(x, y_0, z_0)$,$\Delta D^{MC}_{LOCAL}(x_0, y, z_0)$, and$\Delta D^{MC}_{LOCAL}(x_0, y_0, z)$, where $(x_0, y_0, z_0) = (0, 0, 0)$for Test Cases 1, 2, and 4 and $(x_0, y_0, z_0) = (7\text{cm}, 0, 0)$ for Test Case 3. An example is provided in Figures 3 and 4 (top panels) for Test Case 3.
3. Side-by-side display of $D_{\text{TPS,User}}$ and $\Delta D^{\text{User}}_{\text{LOCAL}}$ 2D dose distribution maps (cGy) in Cartesian coordinate planes passing through the center of the radiation source. The top panels of Figures 3 and 4 provide an illustration again for Test Case 3.
4. Analysis of the $\Delta D^{\text{MC}}_{\text{LOCAL}}$ 2D dose difference ratio distributions in Cartesian coordinate planes passing through the center of the radiation source. This will imply analyzing $\Delta D^{MC}_{LOCAL}(x, y, z_0)$, $\Delta D^{MC}_{LOCAL}(x, y_0, z)$, and $\Delta D^{MC}_{LOCAL}(x_0, y, z)$ where $(x_0, y_0, z_0) = (0, 0, 0)$for Test Cases 1, 2, and 4, and $(x_0, y_0, z_0) = (7\text{ cm}, 0, 0)$for Test Case 3, as seen in Figures 3 and 4 (bottom panels).

5 | LIMITATIONS AND PHYSICIST RESPONSIBILITIES

In general, the AAPM TG-53 report—Quality Assurance for Clinical Radiotherapy Treatment Planning—has clearly outlined the organizational framework for the medical physicist to create an initial commissioning and ongoing QA tasks of the planning process.[40] QA of dose calculations must include not only verification that the dose algorithm works as expected, but also testing other factors that might influence the final dose calculation such as dose grid resolution, density mapping, regions to be calculated, and so forth. Each clinic should consider the relevance for each parameter used when performing MBDCA dose calculation specific to the workflow implemented. The TG-186 report identifies definitive tasks and responsibilities for medical physicists to guide the transition from TG-43 to MBDCAs, but refers back to the TG-53 report for generic operations as described above. We emphasize here the importance of re-commissioning the algorithm when upgrading to a

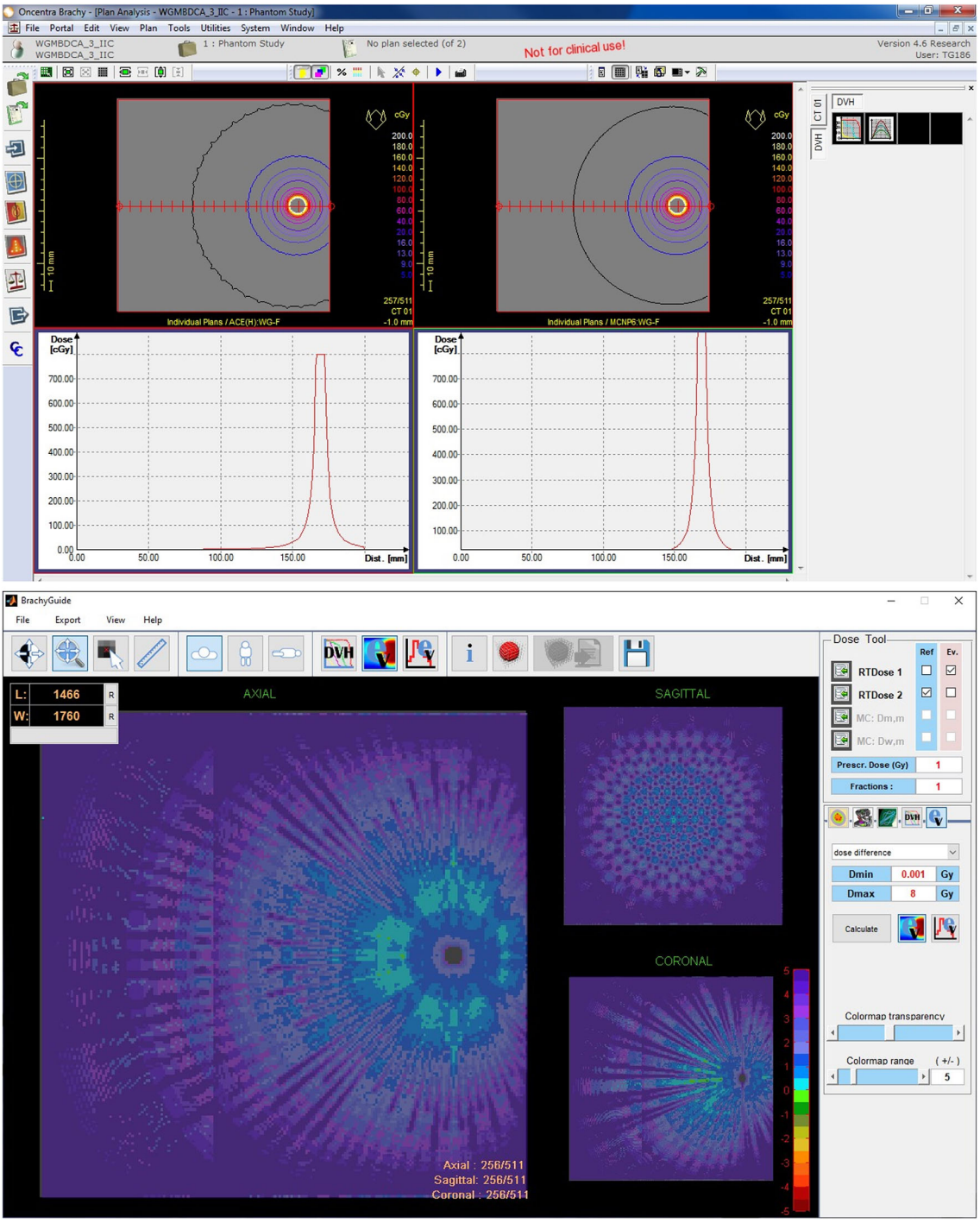

FIGURE 3 Example results of Level 2 testing using Test Case 3: (top) side-by-side display of ACE $D_{TPS,User}$ and $D_{MC,ref}$ 2D dose distributions (cGy) on a plane through the source center along with corresponding 1D dose profiles, obtained using Oncentra Brachy version 4.6. (Bottom) A map of ΔD^{MC}_{LOCAL} differences between ACE $D_{TPS,User}$ and $D_{MC,ref}$ on the same plane, obtained using BrachyGuide.[38]

new or different version of the MBDCA. Annual checks are recommended by repeating the Test Cases 1–4 described above with the expectation of producing similar results.

It is also critical to track the version number of the MBDCA code within the TPS. It is expected that MBDCA methods will continue to evolve and hence TPS re-commissioning is mandated for any changes susceptible to impact the final dose calculation, along with the basic dosimetric comparisons of Test Cases 1–4 between the new and old MBDCA versions. When a new version of a brachytherapy TPS becomes

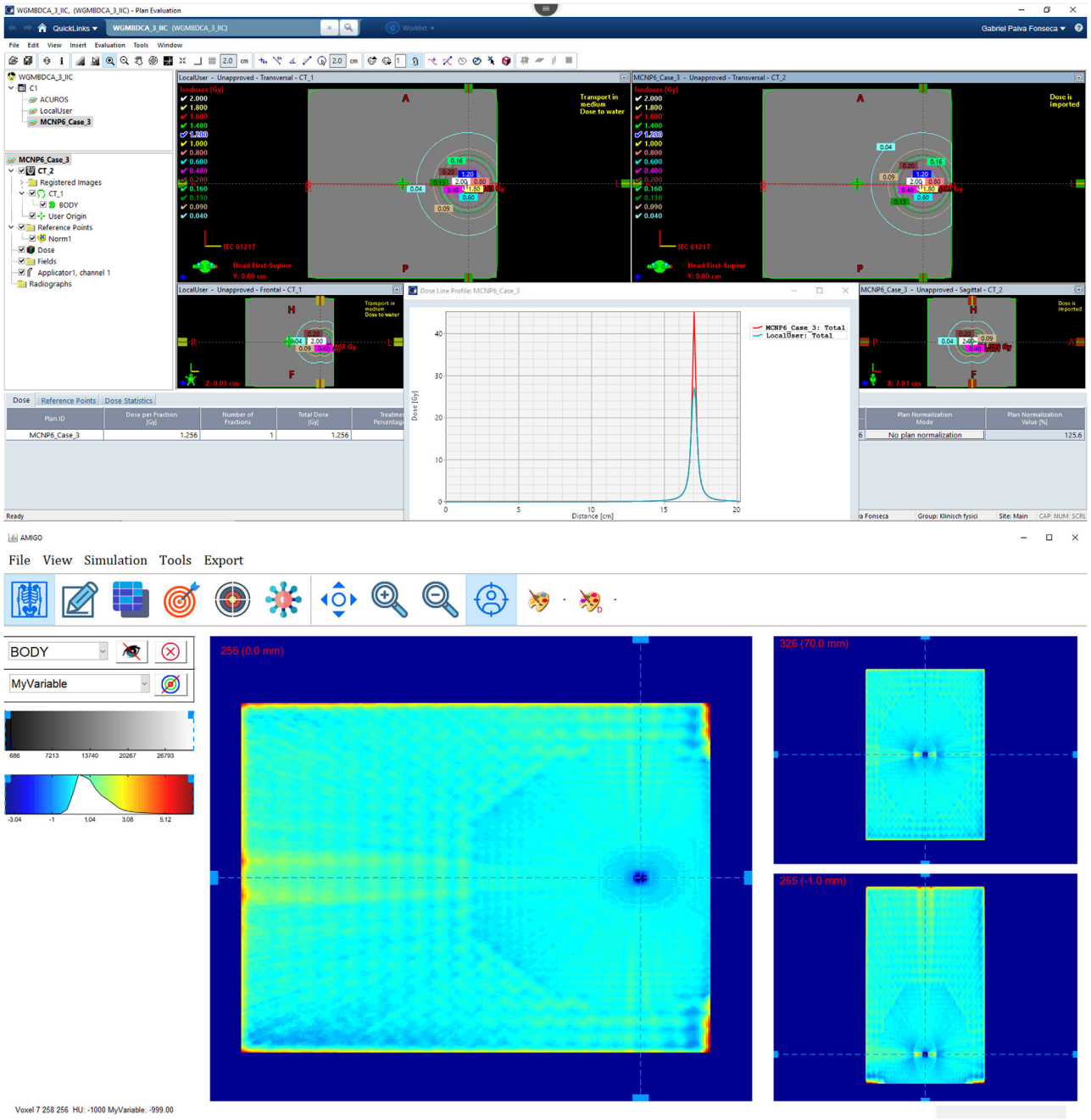

FIGURE 4 Example results of Level 2 testing using Test Case 3: (top) side-by-side display of AcurosBV $D_{TPS,User}$ and $D_{MC,ref}$ 2D dose distributions (cGy) on a plane through the source center along with corresponding 1D dose profiles, obtained using BrachyVision version 15.5. (Bottom) A map of ΔD^{MC}_{LOCAL} differences between AcurosBV $D_{TPS,User}$ and $D_{MC,ref}$ on the same plane, obtained using AMIGO.[39].

available, two scenarios can be expected related to MBDCA algorithms: (1) no change in the code base such that no differences with the available TPS-specific reference data sets is seen when performing the commissioning. (2) One or more changes in the algorithm or related code that lead to differences relative to the available TPS-specific reference data sets from prior versions. In this case, the available MC data sets, along with the TPS-specific data sets from the previous versions can be used to effectively track the magnitude and direction of any change. Therefore, it is recommended that the differences among versions be documented both relative to MC and to a prior version of the TPS-specific data sets. Three outcomes might emerge for this scenario: the new version is closer to MC (the new algorithm/code marks an improvement), is worse than the previous version, or produces mixed results (better in some circumstances but worse in others). Ideally,

such changes should already have been documented and communicated by the vendors and, if not, should be reported for further confirmation. This WG report emphasizes that the vendor should perform internally the process detailed in this report and clearly indicate in their document if the existing IROC Houston-hosted TPS-specific data sets from the previous version of the code remains valid. If not, it should be the responsibility of the vendors to provide new TPS-specific data sets for evaluation by the WGDCAB.

At this time, not every brachytherapy TPS has all the tools necessary to perform an in-depth comparison of 3D dose distributions according to the recommendation of Section 4, as noted in Section 3.3. The TG-186 report already had recommendations for the vendors of MBDCA and most of these tools are available on the EBRT TPSs from the same vendors. This report emphasizes, once more, that modern 3D dosimetry in brachytherapy has the same needs and that these tools should be implemented as soon as possible. In the meantime, the User Guides explain how to accomplish key steps of the recommendations, including validation of the dose at predetermined points and exploring dose difference maps. Until the vendors implement all the necessary tools, this report further recommends that the end-users adopt freely available third-party software such as SlicerRT[41] or brachytherapy-specific tools such as BrachyGuide[38] and AMIGO[39] to enable more in-depth comparison of dose distributions generated by the TPS MBDCA (or TG-43) to reference MC datasets.

While the current report is limited to the four test cases presented, new test cases for ^{192}Ir brachytherapy or other low-energy HDR and low-dose rate (LDR) treatments could benefit from the same infrastructure and workflow. For example, a hybrid-MC MBDCA has recently become available for a low-energy electronic brachytherapy system (INTRABEAM, Carl Zeiss Meditec AG, Germany),[7] but little has been published on this algorithm. The WGDCAB is currently developing new clinically relevant test cases (GYN, head and neck, breast, and prostate) for the existing MBDCA TPS as well as some low-energy test cases for TPSs in development. A good example of such a clinically oriented test case for breast brachytherapy is based on the geometry published by Peppa et al.[42] These will all be added to the Registry once available and fully tested.

This report does not address certain other key issues raised in the TG-186 report.[3] Namely, it does not address CT Hounsfield unit (HU) to material conversion on an individual patient basis, especially relevant for low energy sources, nor does it address the potential need for changes in dose prescription or organ-at-risk dose constraints resulting from MBDCAs. For the time being, the TG-186 recommendations on these two topics stand.

Preceding clinical implementation yet following the commissioning tests performed for a new version of a MBDCA algorithm, any differences impacting the dose distributions outside the regions of immediate clinical interest (including low dose regions) should be communicated to the radiation oncologist. This should be done to ensure that no systematic discrepancies are introduced into the intermediate to low-dose regions away from the brachytherapy target, but still close enough to yield a contribution to a larger volume also treated with EBRT. An example would be nodal boosts with IMRT or VMAT in combination with cervical cancer HDR brachytherapy.

6 | REGISTRY DATA FOR RESEARCH AND EDUCATIONAL ACTIVITIES

The MBDCA commissioning data available on the Registry may be useful in diverse research activities. For example, data may be used for validation/verification of the results of researchers implementing their own MBDCA. Codes or input files may also be used as a starting point for further calculations, for example, using source and/or applicator models in new/different patient geometries or as the basis for developing new models. As an educational tool, it provides well-defined geometry and dose references to those learning the MC method and its application to brachytherapy.

Source, applicator, and test case codes are available for the following MC codes: egs_brachy,[43] Penelope,[44] MCNP6,[45] ALGEBRA,[46] and GEANT4.[47] Each file includes a header indicating the version of the MC code used for the original calculations. Further details on the geometry, including source positioning and orientation for each Test Case, can be found in one of the User Guide described earlier in this report (and found on the Registry[34] along with the data sets).

The following disclaimer is made and included in the Registry: "The AAPM and the IROC Houston QA Center (IROC Houston) maintain this Registry solely as a service to their members and clients. Neither the AAPM nor IROC Houston endorses or approves specific products. No statement regarding the accuracy of the WGMBDCA HDR Ir-192 generic source model definition files provided by the vendor is expressed or implied by inclusion of the source model definition files in this Registry. The AAPM, IROC Houston, Elekta Brachytherapy, and Varian Medical System neither warrant nor are responsible for the consequences of use of the HDR Ir-192 generic source model definition files." The Registry shall be the only repository for the verified source, applicator, and test case codes. Redistribution of the source, applicator, and test case codes obtained from the Registry is not permitted.

7 | SUMMARY OF RECOMMENDATIONS

The recommendations made in this joint report are specific to the MBDCA for brachytherapy. General TPS commissioning recommendations such, as those described in the TG-53 and TG-186 Reports,[3,40] remain valid. The current Report embraces and extends the infrastructure put into place for TG-43.[2]

7.1 | For clinical users

- Review the TG-186 Report,[3] the current Report, and the specific literature pertaining to the MDBCA included in your clinical TPS. The latter includes the underlying physics model, benchmarking works, and clinical applications.
- Follow the proposed workflow and download the MBDCA reference datasets and User Guide for your particular TPS from the Registry.[34]
- Validate the overall setting by performing dose calculations under TG-43 conditions (Level 1).
- Benchmark the advanced dose calculation features using the provided test cases, following the process described in the workflow diagram (Figure 2) of this Report. A step-by-step description of the process is provided in the TPS-specific User Guide.
- Document thoroughly and investigate any deviation from the recommended tolerances (see Section 4).
- It is considered good practice to retrospectively proceed to a recalculation of a few representative past cases in your clinic to document the impact of the more accurate MDBCA.
- The workflow recommended in this Report should be performed when a new TPS version is installed, and/or for any changes susceptible to impact the final dose distribution.

7.2 | For vendors

- Provide basic training on the various TPS features, including the MBDCA.
- Make sure that their MDBCA complies with the TG-186 recommended material composition assignments and dose reporting scheme, in particular $D_{m,m}$.
- Provide all the tools necessary to implement the workflow described in Figure 1 as well as the analysis tools that enable the clinical users to perform all the quantitative comparisons described in the workflow diagram (Figure 2) and Section 4.
- When a new version of the MBDCA is available, provide new TPS-specific datasets for evaluation by the WGDCAB.

7.3 | Other recommendations

The current Report details the MBDCA commissioning process, first schematically described in the TG-186 Report. With the advent of the infrastructure described in this proposal, some TG186 recommendations can be further elaborated upon.

- As a reminder, in the absence of widespread clinical methods for extracting tissue composition directly from medical imaging, the TG-186 recommendations for material composition assignments (density and effective Z) remain the standard for MBDCA.
- For any clinic that has access to a MBDCA commissioned according to the recommendations in this report, $D_{m,m}$ should be reported alongside TG-43 results. This brings consistency with external beam practice as per the TG-329 Report.[48,49]
  - If a clinic has performed an in-depth MDBDCA versus TG-43 comparison and knows the correspondence between the two (target, OARs, dose prescription level), MBDCA could be further used for optimization of treatment plans.
    - The TG-43 approach should still be used as a sanity check with historical data.
- The reporting of the more accurate MBDCA calculated dose should become mandatory for all brachytherapy clinical trials (alongside TG-43 results).
- Finally, after over a decade of brachytherapy MBDCA being available to clinical users, this Report recommends that professional societies issue clinical guidelines pertaining to the necessary dose levels for specific anatomic sites and disease stage in collaboration with radiation oncologist experts.

8 | CONCLUSION

This report presents a general framework for commissioning MBDCAs and constitutes an important part of the delivery of the charges given to the joint AAPM-ESTRO-ABG-ABS MBDCA WG. It is based on the availability of vetted datasets and built upon a process and infrastructure already well-known to medical physicists for consensus brachytherapy source data. As such, it embraces and extends prior work established for the TG-43 formalism. As with many aspects of radiotherapy, the ultimate responsibility to make sure that these new algorithms work as intended rests with the qualified medical physicist. In support of that mandate, this report provides expert-generated test cases and user guides. It is impossible to anticipate all possible situations where MBDCAs might fail. However, while clinical geometries are planned to be added to the Registry, the initial test cases presented in this report remain simple, albeit relevant geometries. It is crucial that the end-user

understands the basic physical principles behind these algorithms as well as their various strengths and limitations. The approach proposed here is twofold: validation that an algorithm performs as intended, and guidance on how to interpret any discrepancies that occur. Thus, the report is as much an educational resource to help the user to better understand their MBDCA as a commissioning guideline. Both of these aspects, combined with other recommendations in the TG-186 report, should serve to build confidence and encourage thoughtful clinical adoption of the new generation of dose calculation algorithms in brachytherapy.

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CONFLICT OF INTEREST STATEMENT

The authors of this report have worked closely with both Elekta and Varian to ensure that key elements of the report were implemented in their respective TPSs. Furthermore, both Elekta and Varian provided access to their TPSs for validation purposes. This was done with the understanding that none of the authors endorsed a specific product. Potential conflicts of interest related to the subject matter of this report are detailed in the following. L. Beaulieu was the holder of an Elekta's research contract related to the early validation of ACE (2014) as well as the recipient of an unrestricted educational grants from Elekta unrelated to the content of this report. F.-A. Siebert received speaker fees from Varian for presentations on brachytherapy TPSs, but not directly related to this work. F. Ballester received research funding from Elekta, which is unrelated to the content of this report. F. Mourtada is the American Brachytherapy Society (ABS) Chairman of the Board (2021). P. Papagiannis was the holder of a research grant from Varian for the independent validation of AcurosBV-based dosimetry calculations in brachytherapy (2008–2011) and he is granted complimentary access to an Oncentra-ACE TPS by Elekta for research purposes. F. Verhaegen and G. Fonseca received research funding from Varian Medical Systems unrelated to the subject of this report. R. Thomson received funding from Eckert & Ziegler BEBIG unrelated to the contents of this report. Å. Carlsson-Tedgren, D. Granero, A. Haworth, M. Rivard, R. Smith, R. Sloboda, and J. Vijande declare no conflicts of interest. The Chair of the Working Group on Model-Based Dose Calculation Algorithms in Brachytherapy has reviewed the required Conflict of Interest statement on file for each author of this report and determined that disclosure of potential Conflicts of Interest is an adequate management plan. Disclosures of potential Conflicts of Interest for each author of the report are found at the close of this document.

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