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Radiotherapy deficiencies identified during on-site dosimetry visits by the IROC HoustonQA Center

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Abstract

Purpose—To review the dosimetric, mechanical, and programmatic deficiencies most frequently observed during on-site visits of radiotherapy facilities by the Imaging and Radiation Oncology Core Houston office (IROC Houston).

Methods—IROC Houston's findings between 2000 and 2014, including 409 institutions and 1020 linacs, were compiled. IROC Houston's on-site evaluation includes verification of absolute calibration (tolerance of $\pm 3\%$), relative dosimetric review (tolerances of $\pm 2\%$ between TPS calculation and measurement), mechanical evaluation (including MLC and kV-MV evaluation against TG-142 tolerances), and general programmatic review (including institutional QA program versus TG-40 and TG-142).

Results—An average of 3.1 deficiencies was identified at each institution visited, a number that has decreased slightly with time. The most common errors are tabulated, and include TG-40/ TG-142 compliance (82% of institutions were deficient), small field size output factors (59% of institutions had errors $\geq 3\%$), and wedge factors (33% of institutions had errors $\geq 3\%$). Dosimetric errors of $\geq 10\%$, including in beam calibration, were seen at many institutions.

Conclusions—There is substantial room for improvement of both dosimetric and programmatic issues in radiotherapy, which should be a high priority for the medical physics community. Particularly relevant was suboptimal beam modeling in the treatment planning system and a corresponding failure to detect these errors by not including TPS data in the linac QA process.

Keywords

IROC Houston; errors; quality assurance; audit; dosimetric review

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Introduction

The mission of the Imaging and Radiation Oncology Core Quality Assurance Center in Houston (IROC Houston), formerly the Radiological Physics Center, is to ensure that institutions deliver high quality (i.e., accurate and consistent) radiotherapy in support of clinical trials. High quality radiotherapy is critical for clinical trials because it maximizes efficiency by increasing the study's power.[1] It is also important in terms of patient outcomes: TROG 02.02 for example, was a study of oropharyngeal cancer with or without an anti-hypoxic agent where all patients received standard of care radiotherapy. Ultimately, the quality of radiotherapy had a greater effect on overall survival than even the hypothesized effect of the pharmaceutical agent at the heart of the study [2]. Quality radiotherapy is critically important to patient outcomes and to the advancement of radiotherapy practice.

Dosimetry on-site visits are IROC Houston's most comprehensive tool for evaluating dose delivery. In this program, an IROC Houston physicist travels to an institution and performs several days of intensive dosimetric measurements as well as programmatic review. In particular, such an audit reviews beam calibration, measured relative dosimetry versus that calculated by the treatment planning system, machine mechanical performance, and programmatic issues such as compliance with TG-142 [3]. Although the exact suite of tests conducted has evolved over the years, these tests are all conducted in a highly consistent manner by IROC Houston physicists with independent dosimetry equipment.

We previously published results from on-site visits focusing specifically on small field dosimetry and indicating frequent errors [4], and more recently relative dosimetric errors associated with Varian accelerators [5]. In this work we more broadly review the most common dosimetric and programmatic problems found during the past 15 years of IROC-Houston's site visit program. As outlined in the AAPM task group 100 report [6], this information should guide physicists, clinicians, and administration in terms of what aspects of a radiotherapy program are most often deficient (i.e., the occurrence of specific failure modes) and therefore likely warrant additional care.

Methods

Importantly, while some IROC Houston site visits were prompted by suspected dosimetric issues, this was rare because most dosimetric issues can be (and were) resolved remotely using other, less intensive, methods. Rather, site visits were overwhelmingly prompted by routine monitoring of those institutions accruing the most patients to clinical trials; institutions where no dosimetric or programmatic issues were suspected. Reports for site visits occurring between 2000 through 2014 (before which machines begin to resemble current systems less and less, and after which site visits were no longer routinely offered because of budgetary constraints) were abstracted, including 409 institutions with 1020 linacs. Dosimetric or programmatic deficiencies identified at each visited institution were compiled.

The test suite included in an IROC Houston on-site audit has evolved over time (e.g., to include MLC (n=45 institutions, 71 linacs) and IGRT evaluations (n=32 institutions, 50 linacs), and replacing TG-40 [7] tests and criteria with TG-142 [3] requirements), and some tests are only conducted at a subset of institutions: brachytherapy evaluations were done only at those institutions that had an HDR or long-half-life LDR program (n=249). However, all measurements and evaluations conducted during a site visit were made in a consistent manner, with measurements using independent equipment brought by IROC Houston physicists. An institutional deficiency was defined when a dosimetric parameter or programmatic process did not meet established standards. These standards were typically based on published guidelines (e.g., TG-142 recommendations for QA [3], or relative dosimetric accuracy of $\pm 2\%$ based on TG-65 [8]) or achievable levels of accuracy based on decades of auditing experience. All results are presented as the number and percent of the institutions and machines receiving a recommendation for each test conducted.

During an on-site audit, dosimetric evaluation of all beams of all machines was conducted. The test suite is comprised of: 1) an intercomparison of IROC Houston's and the institution's primary dosimetry system (including thermometer and barometer), 2) absolute calibration (i.e., TG-51 [9]) with a tolerance of $\pm 3\%$ ($\pm 5\%$ for brachytherapy source strength), 3) relative dosimetric measurements (comparing treatment planning system calculations versus IROC Houston measurements) with a tolerance of $\pm 2\%$. Relative dosimetric measurements for photon beams included point measurements of percent depth doses (between d_{max} and 20 cm depth, for field sizes between 6 cm $\times$ 6 cm and 20 cm $\times$ 20 cm), off-axis factors at d_{max} (from 5 cm to 15 cm from the central axis), output factors for square fields defined by the jaws (between 6 cm $\times$ 6 cm and 30 cm $\times$ 30 cm), "small field" output factors for square fields defined by the jaws and MLC together (between 2 cm $\times$ 2 cm and 10 cm $\times$ 10 cm), additional "small field" output factors for Varian accelerators where the jaws defined a 10 cm $\times$ 10 cm field and the MLC-defined smaller segments (between 2 cm $\times$ 2 cm and 10 cm $\times$ 10 cm) [4], and wedge factors on central axis (for 45° and 60° wedges for field sizes between 6 cm $\times$ 6 cm and 20 cm $\times$ 20 cm, and at depths between 5 cm and 15 cm). Relative dose measurements for electron beams also included cone factors ($\pm 2\%$ tolerance) and PDD measurements (R_{80} and R_{50}) with a 3 mm distance to agreement tolerance. 4) The institution's quality assurance program as compared against TG-40 before 2009 and against TG-142 after 2009 with a binary scoring of whether each test was completed or not at the recommended frequency, 5) mechanical tests including an evaluation of lasers, optical distance indicator, jaw setting indicators, radiation versus light field congruence, a picket fence test for MLC evaluation, and an IGRT-based positioning test [10]. Tolerances for these mechanical tests were based on TG-40/TG-142 criteria. And 6) other clinical practice concerns identified during the on-site audit, such as poor beam-data management (e.g., maintaining two disparate sets), use of damaged or broken equipment, and inadequate physics staffing levels (which was subjectively assessed, but for which an extreme understaffing was required before a deficiency was issued). Evaluations of clinical practice were based broadly on relevant AAPM reports and guidelines as well as IROC experience and data [e.g., 4, 11–13].

Results

A total of 1280 dosimetric and programmatic issues outside of tolerance were reported at the 409 institutions evaluated (3.1 deficiencies per institution on average). The 15 most common deficiencies discovered during site visits are shown in Table 1, which highlight the fail rates per institution or linac. While complete compliance with TG-40/TG-142 was the most common issue (less than 20% of institutions had a QA program fully compliant with TG-40/TG-142), several relative dosimetric deviations of at least 3% were quite common. Small field output factors (particularly those defined by the MLC) have previously been shown to be poorly calculated by the TPS [4,5], and were found to be the most common overall dosimetric failure (59% of the institutions were outside of tolerance). However, wedge factors and off-axis factors were erroneous at approximately 1 in 3 and 1 in 5 institutions each, respectively. An error of at least 4% in the calibration of at least 1 electron beam was also found at more than 20% of institutions. Photon beam calibration errors (4%) were discovered at 8% (n=32) of the institutions visited.

Institutions' primary ion chamber and electrometer systems overwhelmingly showed good agreement with IROC Houston dosimetry systems due to regular ADCL calibration. However, temperature/pressure deficiencies were identified at 11% (n=44) of institutions. Three quarters (33) of these temperature/pressure deficiencies were related to the assessment of pressure, including failure to apply gravity or temperature corrections when using a mercury barometer (introducing a ~0.4–0.5% error; n=12), or having a poorly calibrated digital or aneroid barometer (inducing errors of ~1–2.5%; n=19). The high frequency of observed barometer errors, coupled with their direct impact on beam calibration, reinforces the need to have regular calibration or cross-calibrations between different types of barometers.

Figure 1 shows details of the dosimetric errors: the worst result (for photon, electron, and brachytherapy modalities) outside of criteria for calibration (Figure 1a) and output factors (Figure 2a) at each institution. If an institution had multiple electron beams outside of tolerance (i.e., 4% error), for example, only the single worst electron result is included in Figure 1a. Electron calibration errors were most often seen at the lowest and highest energies. For the high energies, the error was frequently attributed to incorrect overestimation the $PDD(d_{ref})$ by the institution (e.g., using a value of 98% when in reality it was closer to 95%). For both photons and electrons, while some calibration errors were ultimately attributed to single large errors (such as setup errors by the institution during TG-51), most often they were the result of a series of smaller errors (0.5–2%) that all summed in the same direction, demonstrating the importance of managing all, even relatively small, sources of uncertainty in the calibration process.

Figure 1b shows similar results for output factors. More than 10% of institutions had 7% or larger error in their small field output factors, and multiple institutions had errors in excess of 20% between their TPS calculation and their actual output factors.

It is of interest to know how the error rates have changed with time, and the raw rate of deficiencies (of all types) are shown in Figure 2a. Based on regression analysis, the

deficiency rate per visit has decreased with time ($p=0.004$), but the deficiency rate per machine has not ($p=0.6$). The interplay of different specific deficiencies is shown in Figure 2b for key deficiencies, with regression analysis done to test their dependence on time. Institutional deficiencies have decreased largely because of a decrease in “using outdated calibration protocol” – a recommendation given to institutions still using TG-21, which has become less common with time ($p=0.0009$). Machine-specific deficiencies have decreased for some tests, including electron calibration ($p=0.0001$) and wedge factors ($p=0.008$), but the introduction of the “small field” output factor test (and the high rate of problems associated with this test) have offset these improvements, resulting in no net change per machine. There has been no change in the frequency with which QA ($p=0.2$) or photon beam calibration ($p=0.4$) was found to be deficient.

As failure to comply with TG-40/TG-142 was identified as the single most common deficiency, this issue was explored in more detail. As TG-142 is the current standard, results shown in figure 3 are limited strictly to institutions evaluated against this standard ($n=89$). While Table 1 simply identified that institutions did not complete the entirety of this QA, the degree of non-compliance is shown in Figure 3, which shows the percent of QA tests relevant to the institution that were not performed by the institution. Many institutions, 41 out of 89, were not conducting substantial ($>10\%$) sections of TG-142. The tests most often excluded by institutions in their linac QA program are shown in Table 2, which includes tests difficult to implement (off axis factor versus gantry angle), tests not done at the recommended frequency (weekly picket fence), tests perceived to add limited value (MLC transmission), or tests that were simply overlooked (backup monitor constancy).

It is of interest if poor compliance with TG-40 or TG-142 QA is predictive or not of other deficiencies. While institutions that were scored as deficient in their compliance with TG-40/142 ($n=337$) did have more dosimetric deficiencies than those with comprehensive QA programs (2.32 average additional deficiencies versus 2.21), this difference was not statistically significant ($p=0.6$; t-test). This trend was also seen specifically for TG-142 compliance: institutions had more additional deficiencies (1.83 versus 1.33) when they were not compliant with TG-142, but again, this result was not statistically significant ($p=0.2$; t-test).

Discussion

Numerous deficiencies were identified during IROC Houston site visits. Of these, dosimetric errors (i.e., outside the 3% calibration or 2% relative dosimetry tolerances) are often the most concerning because of their direct impact on patient care, i.e., dose delivery. While a given clinical treatment plan may or may not be substantially impacted by a specific error in an individual basic dosimetry parameter, basic dosimetric errors such as those evaluated in the current study have been shown to routinely manifest as problems in clinical plans [14,15]. Moreover, good dosimetric agreement should be achievable overall for this test suite because the test suite includes only relatively simple conditions: only square fields, no extremely large or small fields, and no superficial or extremely deep locations. In addition to the test suite being reasonable, the tolerances are also believed to be reasonable, having been adopted by the physics community as a minimum practice standard [16]. Therefore, the

dosimetric deficiencies in particular must be viewed as cases where systems are not meeting reasonable and minimal expectations. These issues are particularly concerning because the measurements performed evaluate basic dosimetry that is the foundation of more advanced radiotherapy programs such as IMRT. Given the prevalence of issues identified during site-visits, it is perhaps not surprising that there are so many problems with anthropomorphic phantom irradiations[17], and that these problems with phantom irradiations appear to originate with errors in dose calculations[18,19]. Regardless of the treatment modality, it is concerning that such frequent problems were identified.

When a disagreement is found between the TPS calculation and IROC measurement such a wedge factor or PDD, it is standard practice for IROC to investigate this disagreement. For relative dose, this includes reviewing the institution's commissioning and annual QA measurements. If the institution's measurement and their TPS calculation agree, but IROC's measurement disagrees, that generally indicates an issue with commissioning. If the institution's and IROC's measurements agree and the TPS calculation doesn't agree with either, this indicates a problem with the beam modeling in the TPS. Although the specific results of these follow up investigations are not recorded and therefore can't be quantified in this report, for the vast majority of cases, the IROC measurement and the institution's commissioning/QA measurements agreed very well. That is, there was very rarely disagreement between IROC and the institution in terms of measured dose distribution, and very rarely was there evidence of errors during commissioning. Rather, all IROC physicists report that the overwhelming finding was that the TPS calculation disagreed: beam modeling was consistently observed to be the predominant problem in cases of dose calculation errors. Consequently, it is critical to maximally include the TPS beam model into the quality assurance program. One important and easy to implement method is to ensure that TPS calculated doses are used as the "baseline" values during monthly and annual linac QA tests, rather than commissioning data (or other previous measurements). Such an approach would readily catch a substantial fraction of the errors in basic dosimetry observed during IROC site visits.

A commonly observed programmatic deficiency was compliance with TG-40/TG-142. While it would be satisfying for comprehensive linac QA to result in good dosimetric agreement, this was not statistically supported as failure to comply with these reports did not statistically predict dosimetric problems (although the power of this comparison is lessened by the small number of institutions that complete the entirety of the QA recommendations). Anecdotally, there was almost never a direct cause and effect observed between poor linac QA and poor dosimetric performance. Dosimetric errors were very rarely associated with changes in linac performance (meaning that more linac QA wouldn't have caught the error). Rather, as discussed in the previous paragraph, the TPS calculation had never agreed with the actual dose distribution generated by the linac, and the error had typically never been identified because the TPS calculation was never incorporated into the QA program. Naturally, this doesn't mean machine QA isn't important; many parameters (such as output) do drift and need to be properly maintained [20,21], and many tests in TG-142 were not relevant to the specific tests conducted during the on-site audit so this evaluation does not capture the full impact of a linac QA program. Nevertheless, clear and substantial improvements could be achieved in clinical practice by focusing relatively more medical

physics effort on the TPS beam model commissioning and QA (e.g., MPPG5a [16] and TG-53 [22]) and directly linking these calculations to machine QA tests.

Dosimetric errors are ultimately the responsibility of the institution to rectify (following their confirmation of the issue). In practice, implementing this is often done with great reluctance, likely because it may be an intimidating prospect to modify the TPS beam model. To be sure, it is critical that any change in the beam model does not make the overall agreement poorer! However, ensuring that the right dose is delivered to the patient is one of the most fundamental tenets of the medical physics profession, and this requires an accurate beam model.

Extensive additional analysis is warranted, including the influence of institutional parameters on discrepancies, the age of equipment, types of equipment, etc. This will be the focus of a future study.

Conclusions

The prevalence of dosimetric and programmatic deficiencies across radiotherapy facilities is high. Rectifying these issues should be a high priority for the medical physics community. Dosimetric errors usually originated with the TPS beam model, and more focus and attention should be given to beam model commissioning and QA to ensure that it accurately describes the radiation beam(s) for the relevant linac(s). It is particularly important to include the TPS calculations in the machine QA process, that is, monthly and annual linac QA measurements should be compared against the TPS, not against commissioning data.

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Summary

IROC Houston on-site visits of radiotherapy facilities includes an evaluation of beam calibration, relative dosimetry, mechanical checks, and other programmatic issues. The deficiencies identified over the past 15 years are compiled in this study, highlighting areas where problems are most often found (e.g., small field output factors, wedge factors, calibration, etc.). These areas should receive particular attention during beam modeling and machine QA by medical physicists to ensure optimal accuracy is achieved.

Figure 1.

The single worst calibration error (a) and output factor error (TPS-calculation versus measurement) (b) for each institution per modality (photon, electron, and brachytherapy for centers with brachytherapy programs (where the tolerance was $\pm 5\%$ compared to $\pm 3\%$ for the teletherapy modalities)). Output factor errors in (b) include “large fields” (jaw-defined output factors for fields $\geq 6 \text{ cm} \times 6 \text{ cm}$), small fields (MLC-defined output factors for fields between $2 \text{ cm} \times 2 \text{ cm}$ and $10 \text{ cm} \times 10 \text{ cm}$), and electron cone ratios.

Figure 2.

a) Overall recommendations versus calendar year. b) Specific recommendations by calendar year.

Figure 3.
Percent of relevant TG-142 QA tests not performed by the 89 institutions evaluated against TG-142.

Table 1

The 15 most common deficiencies (e.g., 4% calibration error or 3% relative dosimetry error) noted during IROC Houston on-site visits, including the frequency by institution and by linac.

Deficiency observed	# Inst. with deficiency	% of Inst. with deficiency	# Linacs with deficiency	% of Linacs with deficiency
TG-40 & TG-142 compliance	337	82	-	-
Small-field output factors *	132	59	165	51
Wedge factor (incl. field size/depth dep.)	134	33	171	17
Off-axis factor	87	21	109	11
Electron calibration	83	20	105	10
Photon PDD	75	18	100	10
Using outdated calibration protocol (TG-21)	70	17	-	-
Electron PDD	47	12	57	6
Temperature/Pressure	44	11	-	-
IGRT isocenter coincidence *	3	9	4	8
Beam symmetry	34	8	44	4
Photon calibration	32	8	34	3
Brachytherapy source calibration *	17	7	-	-
Electron cone factor *	18	6	19	5
Output factor (not "small field")	21	5	24	2

Values are shown as a percent of institutions or linacs that received each test, which was typically all 409 institutions and 1020 linacs. However not all institutions received all tests (e.g., as the test suite evolved, and based on the equipment of the institution) and tests where this occurred are denoted with an *. The least sampled test was IGRT isocenter coincidence, evaluated at 32 institutions (50 linacs).

Table 2

Tests from TG-142 [3] that were most often not conducted by institutions as part of their linac QA program.

Indicated frequency	Type of test	Test	% of inst not performing test
Annual	Dosimetry	X-ray and electron OAF constancy vs. gantry angle	49
Annual	Dosimetry	MLC transmission (ave. of leaf and interleaf trans.- all energies)	39
Monthly	Mechanical	MLC travel speed	37
Daily	Mechanical	MLC qualitative weekly test (matched segments "picket fence")	37
Annual	Mechanical	Coincidence of MLC light field and x-ray field (all x-ray energies)	34
Daily	Mechanical	Dyn./Virt./Univ. wedge check (run for 1 angle)	34
Annual	Mechanical	MLC spoke shot	30
Monthly	Dosimetry	Dyn./Virt./Univ. Wedge factor (all energies)	30
Monthly	Dosimetry	Backup monitor constancy	28
Annual	Mechanical	Moving window IMRT (4 cardinal gantry angles)	27
Annual	Mechanical	Tabletop sag	25
Annual	Other	Comparison to clinical values	25
Daily	Mechanical	Collimator size indicator	25
Monthly	Dosimetry	Typical dose rate output constancy (IMRT and SRS/SBRT)	24
Daily	Safety	Radiation area monitor	24
Monthly	Imaging	Geometry distortion (CBCT only)	23
Annual	Dosimetry	X-ray and electron output vs. gantry angle	21
Monthly	Imaging	HU (CBCT only)	21
Annual	Dosimetry	Physical Wedge factor constancy (FS and depth dep.)	20
Annual	Imaging	Imaging dose	20