Anniversary Paper: Fifty years of AAPM involvement in radiation dosimetry

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This article reviews the involvement of the AAPM in various aspects of radiation dosimetry over its 50 year history, emphasizing the especially important role that external beam dosimetry played in the early formation of the organization. Topics covered include the AAPM's involvement with external beam and x-ray dosimetry protocols, brachytherapy dosimetry, primary standards laboratories, accredited dosimetry chains, and audits for machine calibrations through the Radiological Physics Center. © *2008 American Association of Physicists in Medicine*.
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I. THE IMPORTANCE OF DOSIMETRY IN RADIOTHERAPY AND RADIOLOGY

The most important role of the clinical radiotherapy medical physicist is to ensure the accurate delivery of the prescribed dose distribution to the patient. A critical role for a diagnostic medical physicist using x-ray beams is to minimize the dose to the patient while obtaining a good image. In both cases, the measurement of the doses involved plays a key role in the process and thus radiation dosimetry is one of the central concerns of a clinical physicist. It is therefore not surprising that the AAPM has undertaken a significant role in the area of radiation dosimetry. The purpose of this article is to outline some of the history of the AAPM in dosimetry related to radiotherapy.

The basis for the concern about dosimetry in radiotherapy is the fact that there is a clinical need for accurate dose delivery to the tumor. The often stated goal is for 5% accuracy.[1] To achieve this goal requires accuracy at many steps in the radiotherapy process, from the reference dosimetry which specifies the output from the radiation source in a water tank, to the treatment planning system which calculates the dose distribution in the individual patient, to the patient alignment or the source placement in the patient, to accounting for tumor motion within one fraction or between fractions, and to the accurate control of the radiation delivery. Each of these steps adds uncertainty in the final delivered dose and it has become common in external beam treatments to aim for an accuracy of 1%–2% in the specification of the absorbed dose to water under reference conditions. The advances at standards laboratories, Accredited Dosimetry Calibration Laboratories (ADCLs), and in external beam dosimetry protocols in the last 50 years mean that this goal should be achieved in most external beam situations. The AAPM has played a major role in several aspects of this progress and this role will be reviewed below.

For various reasons the progress in brachytherapy dosimetry has not reached the same level of accuracy. Nonetheless, there has been substantial progress and this will also be reviewed, along with the central role that various AAPM committees have played in this field.

In diagnostic x-ray imaging and radiation protection dosimetry, the need for dosimetric accuracy is not as critical as in radiotherapy since the main goal is to follow the "as low as reasonably achievable" principle. Nonetheless, the issues of dosimetry come up in various ways, from ensuring properly calibrated instrumentation, to deciding how to best quantify the dose to patients undergoing diagnostic examinations and although not covered here, the AAPM has played an important role in this area as well.

In the rest of this article we will review the role of medical physicists and the AAPM over the last 50 years in various aspects of radiation dosimetry with a focus on reference dosimetry. We start with a discussion of the development of external beam dosimetry protocols, both for megavoltage beams, culminating in the TG-51 protocol, and then for x-ray beams, culminating in the TG-61 protocol. The AAPM has played a central role in protocol development which is a very important aspect of radiation dosimetry. Then there is a discussion of the AAPM's role in brachytherapy dosimetry where the approach by TG-43 and its updates are currently the state-of-the-art for the entire world.

All dosimetry protocols start from having an accurate calibration coefficient and this is based on accurate primary standards and an accurate calibration chain. Thus, after discussing protocols for external beams and brachytherapy dosimetry, the next two topics covered are the relationship between the medical physicists in the AAPM and primary standards laboratories and then the role of the AAPM in setting up and accrediting a series of ADCLs which provide high-quality calibrations to the medical physics community.

Finally, the existence of protocols and high quality calibrations does not, on its own, ensure accurate clinical dosimetry. To ensure this for clinical trials (at least), the Radiological Physics Center (RPC) was established at the University of Texas M.D. Anderson Cancer Center in Houston and the AAPM has played an important role in providing oversight and direction to this body which is discussed in the last part of this article.

In this article we have chosen to use current terminology (e.g., calibration coefficient rather than factor) as consistently as reasonable.

II. AAPM AND MEGAVOLTAGE EXTERNAL BEAM PROTOCOLS

Up until the latter 1990s, there was considerable emphasis at annual meetings of the AAPM on all sorts of dosimetry issues since clinical physicists were struggling to sort out how to measure dose accurately in a wide variety of situations. While there are still some unresolved issues regarding measurements in electron beams and perhaps even more issues in small photon beams which are of increasing importance because of stereotactic radiosurgery and intensity modulated radiation therapy (IMRT), the fact that dosimetry research is no longer a major component of the annual meetings is an indication of the degree of success that has been achieved, at least for measurements in water under reference conditions.

II.A. The protocols of the AAPM's Scientific Committee on Radiation Dosimetry

However, this was not always the case. In the early days of megavoltage therapy, a major concern of medical physicists was how to measure absorbed dose consistently between various institutions. Those founding the AAPM 50 years ago had the organization focus a great deal on the issue of dosimetry in megavoltage beams. The first AAPM involvement was through the organization's Scientific Committee on Radiation Dosimetry (SCRAD) which published it's first report,[2] "Protocol for the dosimetry of high energy electrons", in Physics in Medicine and Biology (PMB) which was the official journal of the AAPM from 1964 until the initial volume of the AAPM's journal Medical Physics was published in 1975. As an indication of how important this work was to the founders and early leaders of the AAPM and, hence, to the AAPM, one can note that of the 16 named members of SCRAD, eight of them served as president of the organization seven of them won the AAPM's highest honor, the Coolidge Award, and three won the Award for Achievement in Medical Physics, the organization's second highest honor. Clearly radiation dosimetry was a very high priority for the early members of the AAPM and a central task for clinical medical physicists.

The significant changes in clinical radiation dosimetry since 1966 can be appreciated by looking at the SCRAD protocol of that year. It recommended the use of activation foils as the technique for determining the energy of an electron beam, the use of Fricke dosimetry for absorbed dose calibrations and the use of a Farmer chamber placed at the maximum of the dose distribution in a polystyrene phantom to measure the "output" in "R per minute" based on the chamber's calibration in terms of roentgen in a ^{60}Co beam.

SCRAD followed with a "Protocol for the Dosimetry of X- and Gamma-Ray Beams with Maximum Energies Between 0.6 and 50 MeV" which was published in 1971, again in PMB.[3] This was basically an AAPM protocol which drew heavily on two 1969 protocols, one by the Hospital Physicists Association of Great Britain[4] (HPA) and one by the International Commission on Radiation Units and Measurements (ICRU).[5] This protocol was based on using an ion chamber and the C_λ formalism

$$D = MN_cC_\lambda \ \text{(rad)}, \tag{1}$$

where D is the dose in the water at the midpoint of the chamber, M is the reading on the ion chamber in some units, rdg, when placed in a water or plastic phantom, and N_c is the chamber's ^{60}Co exposure calibration coefficient, in R/rdg. The protocol provided a chamber-independent table of C_λ values based on calculated stopping-power ratios and ratios of mass energy absorption coefficients.

II.B. The AAPM's TG-21 protocol

Shortly after publication of the SCRAD photon protocol it was realized that there was a chamber dependence in the C_λ values which was ignored in the SCRAD protocol and after another 12 years, the AAPM's Task Group 21 produced a completely new class of protocol[6] which was similar to the new protocols being developed in Europe.[7,8] It was still based on an exposure or air-kerma calibration coefficient, but now it was explicitly based on Spencer–Attix cavity theory and recognized many of the chamber dependent aspects of dosimetry. The TG-21 protocol required the user to make many calculations of the correction factors needed for his or her ion chamber. This new protocol was based on a great deal of research by medical physicists that had gone on in the intervening 12 years. In particular, its framework was based on a seminal paper by Loevinger[9] who headed the dosimetry standards group at what was then the National Bureau of Standards [today National Institute of Standards and Technology (NIST)]. The TG-21 protocol used an exposure calibration coefficient to determine the cavity-gas calibration factor, N_{gas}, which is simply $(W/e)_{\text{air}}/m_{\text{air}}$, where m_{air} is the mass of the air in the ion chamber's cavity. In other words, N_{gas} is a constant related to the volume of the chamber. Unfortunately, the expression used to determine N_{gas} is somewhat more complex. Nonetheless, by using this approach and

Spencer–Attix cavity theory with various corrections, the protocol was able to handle dosimetry in both electron and photon beams.

Once again, the roster of TG-21 is indicative of the importance that continued to be associated with radiation dosimetry. Of the eight authors, three were Presidents of the AAPM, five of them were Coolidge Award winners, and one received the Award for Achievement in Medical Physics.

In the 1990s there were two further Task Groups which dealt with dosimetry related issues. The first was the TG-25 report on "Clinical electron-beam dosimetry"[10] which built on the TG-21 foundation and discussed the many issues related to electron beam dosimetry in nonreference conditions (and was headed by another President/Coolidge Award winner). This was an immensely useful and practical report. The report of TG-39 on "The calibration and use of plane-parallel ionization chambers for dosimetry of electron beams"[11] was a highly specialized report on the proper way to calibrate plane-parallel ion chambers which constituted an extension to TG-21.

II.C. The AAPM's TG-51 protocol

One of the main reasons for the complex nature of all the protocols of the TG-21 era was the fact that radiation beam calibrations were based on ion chamber calibrations done free-in-air in terms of air kerma, but the chamber was used in-phantom to derive a reference value in terms of absorbed dose to water. Meanwhile, the primary standards laboratories at NIST, at the National Research Council of Canada and elsewhere were developing a new generation of primary standards for absorbed dose to water based on water calorimeters. The agreement among the various standards had been shown to be within 1%.[12] It was clearly desirable to make use of these new standards and following the lead of a German protocol,[13] the concept of basing a protocol on absorbed dose calibration coefficients was imported to North America.[14,15] This became the basis of a new generation protocol which culminated in the publishing in 1999 of "AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams."[16] This protocol met the objectives of simplifying the process of doing reference dosimetry, primarily by making use of the absorbed dose calibration coefficients, and of increasing the accuracy of the protocol, partially by avoiding the switch of quantities from an air-kerma calibration to an absorbed dose reference quantity and partially by using stopping-power ratios corresponding to realistic electron beams. This protocol has been in use for nearly 9 years now and, as shown in Fig. 1, by July 2007, 88% of all clinics being monitored by the RPC were using this protocol. In the 9 years since the protocol was released there have been no major errors uncovered in the protocol, although there have been improvements in our understanding. The biggest issue at present is that there are various new chambers for which TG-51 has no values of the quality conversion factor, k_Q. Once again the AAPM has setup a working group tasked with providing an extended set of k_Q values. There are also issues revolving around the dosimetry in IMRT beams since the small pencil beams and steep dose gradients can make standard reference dosimetry values inappropriate and the AAPM has a working group looking into this new area.

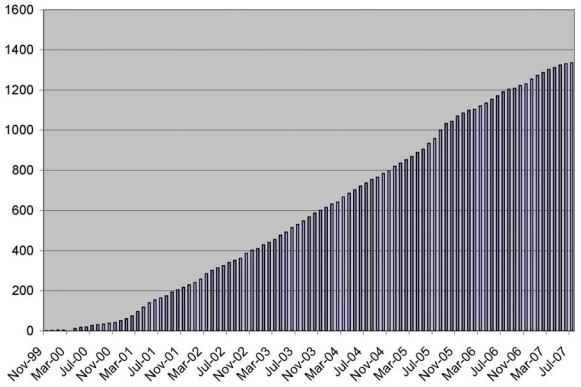

FIG. 1. Data from the RPC showing that 1330/1508 active clinics being monitored in North America had adopted TG-51 by July, 2007.

III. AAPM AND X-RAY DOSIMETRY PROTOCOLS

Soon after its discovery by Roentgen in 1895, x-ray radiation was put into almost immediate medical use. Both the success, like that of the first recorded tumor treatment in 1895, and the failures of those early attempts underlined the necessity for the quantitative measurement of the radiation emerging from an x-ray tube. Although the use of kilovoltage x-ray beams has decreased in external beam radiotherapy as Co-60 teletherapy units and linear accelerators were developed, kilovoltage x rays are still used for treating superficial targets such as skin cancers and in intraoperative radiotherapy.[17] Kilovoltage x rays are also widely used in radiobiology studies for cell and animal irradiation. Therefore, there is the need for accurate dosimetry for kilovoltage x rays.

Kilovoltage x rays have some unique properties compared to high-energy photon and electron beams. For example, knock-on electrons from clinically available 50–300 kV x rays have very small ranges (<0.5 mm of water). Their dose distributions include a significant (up to 30%) scatter component, which is energy and field size dependent. Because of the negligible radiative energy loss for this energy range collision kerma is considered to be the same as kerma and absorbed dose. Commonly used ionization chambers have been generally calibrated as "exposure meters" and used as "photon detectors" since the well-known Bragg–Gray cavity theory no longer applies to this energy range.[18]

The introduction of the roentgen in 1928 at the Stockholm Congress of Radiology marked the beginning of precise physical measurement of the radiation dose, which was later redefined at the Chicago Congress of radiology in 1937 for both x and γ rays. The apparatus used almost universally to measure x-ray dose in accordance with the definition of roentgen was a "free-air" chamber, in which the secondary electrons that produce the ionization originate and complete their tracks in the air of the chamber. Good agreement

(±1%) between the standards chambers of several national laboratories in the energy range of 100–180 kV was reported by Taylor in 1931 but was later shown to be incorrect. Errors in the U.S. and British x-ray standards of the order of 1.5% and 2.5%, respectively, were reported in 1954 by Wyckoff *et al.*[19] American physicists, especially those at the NIST, made major contributions to the standardization of x-ray measurements using free-air chambers as further described in Sec. VI below.

Due to the lack of a North American clinical dosimetry protocol for kilovoltage x-ray beams, a variety of dosimetry procedures were used in practice with a combination of conversion and correction factors measured and/or taken from different protocols. A 1995 survey[20] showed that the most widely used protocol at that time was the 1981 National Council on Radiation Protection and Measurements (NCRP) Report No. 69.[21] The membership of the NCRP report committee included 11 AAPM members: among them were six Coolidge Award winners and six who served as AAPM president. NCRP Report No. 69 provided a formula to calculate the dose to a phantom material at a point in air (with a proper buildup) for tube potentials from 10 kV through the medium-energy range. A backscatter factor, which was not provided in the report, would be needed to calculate the dose on the phantom surface. Some hospitals adopted ICRU Report No. 23,[22] which recommended a backscatter method for the low-energy (40–150 kV) range with the backscatter factors taken from Br. J. Radiol., Suppl 10 (Ref. 23) and an in-phantom method for medium-energy (150–300 kV) x rays. This 1973 ICRU report was prepared by two European task groups, one on measurement of absorbed dose at a point in a standard phantom and the other on methods of arriving at the absorbed dose at any point in a patient. The ICRU report introduced the in-phantom method for dose measurement in medium-energy x-ray beams, which at that time was still widely used for treating deep-seated tumors (therefore the name orthovoltage radiotherapy). A few institutions used the IAEA's TRS-277 Code of Practice,[24] which also recommended the backscatter method for the low-energy range and the in-phantom method for the medium-energy. The backscatter factors for the low-energy formalism were calculated using the Monte Carlo method while the introduction in the medium-energy formalism of a chamber related perturbation correction factor, which was up to 10% near the low-energy end, created some controversies and was later revised. Many studies were carried out in the late 1980s and early 1990s on the various aspects of kilovoltage x-ray dosimetry and an AAPM task group (TG-61) was formed to evaluate the situation and to produce a dosimetry guide for medical physicists in North America.[20]

The 2001 TG-61 report "AAPM protocol for 40-300 kV x-ray beam dosimetry in radiation therapy and radiobiology" is the only AAPM protocol on kilovoltage x-ray dosimetry.[20] The TG-61 report provides detailed recommendations for reference and relative dosimetry, as well as guidelines for clinical dosimetry and quality assurance measurements. TG-61 recommended the backscatter method for the low-energy range (up to 150 kV) and both the backscatter method and the in-phantom method for the medium-energy range (100–300 kV). The uncertainty would be much greater if one derived the dose at a depth based on a surface dose calibration (i.e., using the backscatter method) because of the large uncertainties in the depth dose values near the phantom surface. Comprehensive investigations of the dosimetry consistency between the two dosimetry methods and the results show good agreement for both methods have been carried out using the TG-61 formalism and dosimetric data. Since the TG-61 report was published in 2001 there have been no major errors reported in the protocol.

IV. THE ROLE OF THE AAPM IN STANDARDIZING BRACHYTHERAPY DOSIMETRY

The AAPM has had a major impact on disseminating new scientific developments in brachytherapy dosimetry to the clinical community through an influential series of task group reports that have defined practice standards in this field for nearly 20 years.

IV.A. Early AAPM brachytherapy activities: 1980–1990

The first AAPM guidance document that dealt with brachytherapy in any detail, was its report 13 "Physical aspects of quality assurance,"[25] published in 1984. Its brachytherapy chapter touched upon both calibration and single-source dose computation practices. The report provided detailed guidance on use of reentrant and external ion chambers for transferring calibrations from a standard calibrated source to clinical sources. The report defined direct and secondary traceability of brachytherapy source calibrations by analogy to external beam. It recommended that each institution obtain a reference source with a directly traceable NIST calibration and use the source to transfer this calibration to the chamber. While Report 13 recognized that most commonly used brachytherapy sources were calibrated in terms of exposure rate at a large distance, it hesitated to make any recommendations regarding replacement or even interpretation of units such as milligram radium equivalent and millicurie. No specific guidance on dose calculation methods was given, although both one-dimensional path length models and the possibility of directly measured dose distributions were acknowledged.

In 1987, the AAPM published the Task Group Report 32,[26] which defined the quantity air-kerma strength, and its symbol, S_K. This important report recommended that the new quantity be used for specifying source strength on vendor calibration certificates and as input to computerized dose-calculation tools. TG-32 took the important step of recommending that all clinically-used brachytherapy sources have S_K calibrations that are secondarily traceable to the appropriate NIST standards.

An important AAPM initiative was extending its successful system of ADCLs (discussed below) to include brachytherapy air-kerma strength calibrations. Starting in 1987, some ADCLs were accredited to perform ^{137}Cs source, low dose-rate ^{192}Ir seed, and ^{125}I seed "directly traceable" S_K

calibrations for both reentrant ionization chambers and sources themselves. These services were followed by high dose-rate (HDR) ^{192}Ir, ^{103}Pd interstitial seed, and beta-emitting intravascular brachytherapy calibration services in 1991, 1999, and 2001, respectively. AAPM's definition of "direct traceability" was amended in 1997 by TG-56 (Ref. 27) so that direct traceability was possible through ADCL source and instrument calibrations. The ready availability of relatively cost-effective traceable calibrations was critical to the widespread penetration of NIST-traceable calibration practices into individual clinics.

IV.B. AAPM impact on low-energy photon-emitting source dosimetry

The AAPM's most important contributions to brachytherapy clinical practice have been in areas of low-energy source (^{125}I and ^{103}Pd seeds) dosimetry and source-strength standardization. Its first contribution in this area was the original TG-43 report published in 1995.[28] This report synthesized three important scientific advances of the previous decade. One advance was the development of reproducible methods using TLD dosimetry for measuring absorbed dose in phantom around low-energy and high-energy interstitial sources. A second important advance was introduction of a primary air-kerma strength standard for ^{125}I seeds by NIST,[29] denoted by $S_{K,N85}$ in AAPM guidance documents. When seed strengths are traceable to a stable primary standard that accurately realizes a well-defined physical quantity, theoretical as well as experimental techniques can be used to estimates absolute dose rate. A third advance was the introduction[30,31] and validation[32] of Monte Carlo simulation of photon transport as a brachytherapy dosimetry tool. These techniques helped explain[33] the 10%–18% differences between TLD dose-rate measurements and the predictions of semiempirical dose-calculation models.[34] The historical and scientific analysis of these important developments are reviewed in detail elsewhere.[35,36]

The 1995 report of TG-43[28] proposed a table-lookup dose-calculation algorithm for inferring absorbed dose rates from sparse arrays of measured or Monte Carlo-based single-source doses as an alternative to semiempirical dose-calculation algorithms. In addition, TG-43 reviewed the published TLD and Monte Carlo data available for two widely used ^{125}I sources, one ^{103}Pd source, and one ^{192}Ir source. For each of these sources, a consensus data set was recommended, including dose-rate constants, anisotropy constants and factors, anisotropy functions, and radial dose functions. The TG-43 formalism and the quantity air-kerma strength were embraced in the early 1990s by most researchers in the field. However, TG-43 had relatively little impact on clinical practice until the late 1990s, except for isolated groups of practitioners, e.g., participants in the Collaborative Ocular Melanoma Study were required to adopt TG-43 dose-calculation parameters for ^{125}I eye-plaque therapy in 1996.

The 1995 TG-43 recommendations implied that ^{125}I dose rates were 10%–15% lower than those given by then current dose-calculation practices. The 1999 implementation by NIST of a new air kerma strength primary standard based on a wide-angle free air chamber (WAFAC), $S_{K,N99}$ (Ref. 37) necessitated another 10% change, but in the opposite direction. Because the potential for error was high in simultaneously modifying the source-strength and absorbed dose scales by more than 10%, the AAPM created an Ad Hoc Working Group to assist the community in adapting to these changes. The Working Group report[38] developed a step-by-step procedure for implementing the new WAFAC standard and the TG-43 formalism and recommended that the ^{125}I monotherapy prescribed dose be revised from 160 to 145 Gy. It appears that the complexity of these changes motivated the community and planning software vendors to belatedly but rapidly adopt the TG-43 dose-calculation formalism.

As a result of the rapid shift from radical prostatectomy to permanent seed implantation as the dominant modality for treatment of low risk prostate cancer, commercially available seed products began to proliferate from 3 in 1999 to over 20 in 2004. While the WAFAC $S_{K,N99}$ standard allowed these sources to be efficiently added to the system of traceable calibration quantities, the field was swamped by multiple dosimetry publications (as many as 20 different publications on the 6711 seed alone). Recognizing that these developments had the potential to cause significant confusion and dose-delivery errors, in 1997 the AAPM created a permanent Working Group on Low Energy Interstitial Brachytherapy Dosimetry or LIBD which is currently named "Brachytherapy Subcommittee (BTSC)."

BTSC took an active role in the introduction of new source-strength standards and revised dosimetry practices, coordinating efforts of NIST, source vendors, the clinical community, and ADCLs on a source model-by-model basis. A particularly complex challenge, both technically and politically, was coordination of community-wide implementation of the $S_{K,N99}$ primary standard for ^{103}Pd seeds in 1999. There had been no traceable standard of any kind between 1987 and 1999. BTSC performed a careful historical assessment of "administered-to-prescribed" dose ratios that enabled users to duplicate dose delivery practices of the past in the face of multiple revisions to the ^{103}Pd dosimetry parameters, seed design changes, and calibration changes both by the vendor and NIST.[39,40] This task was initially complicated by differences between vendor and NIST calibrations exceeding 25%. Successfully orchestrating an orderly community response and adaptation to the growing complexity of clinical brachytherapy dosimetry was a major achievement of the AAPM.

BTSC devised a set of dosimetry guidelines,[41] recommending that every routinely used low-energy interstitial source product have a NIST-traceable S_K vendor calibration process and independent experimental and Monte Carlo dose-rate evaluations as documented by peer-reviewed publications. These guidelines have become de facto industry standards, accepted by nearly all vendors involved in the market. Finally, BTSC collaborated with the Calibration Laboratory Accreditation Subcommittee to develop a protocol requiring periodic intercomparisons at 6 month intervals between NIST, ADCLs, and low-energy seed vendors. Com-

pliance with this protocol is now required for a seed model to be posted on the online seed registry as compliant with AAPM dosimetry recommendations, to have data tabulated in AAPM TG-43 supplements, or to be used in National Cancer Institute (NCI) multi-institutional trials.

Another BTSC contribution was a major revision of the TG-43 dose-calculation protocol in 2004,[42] including consensus dosimetry parameters for eight source models. An uncertainty analysis demonstrated that the uncertainty of Monte Carlo-based transverse-plane absolute dose distributions was 3%–5% compared to 8%–10% for TLD dosimetry.[36,43] Because Monte Carlo dosimetry is subject to potentially large and unpredictable systematic errors (e.g., errors in implementation of the S_K standard or presence of contaminant radionuclides, etc.), both experimental and Monte Carlo dose-rate characterization continue to be indicated, at least for low-energy sources. A supplement to the revised TG-43 protocol, including consensus dosimetry parameters for an additional eight source models, was published in 2007.[44]

IV.C. AAPM and higher-energy photon-emitting brachytherapy dosimetry

The 1997 report of Task Group 56, "Code of practice for brachytherapy physics,"[27] provides the most comprehensive guidance on high-energy source dosimetry, which includes all sources emitting photons with mean energies greater than 50 keV, but in practice is limited to ^{192}Ir, ^{137}Cs, and more recently, ^{169}Yb sources. It includes guidance on end-user calibration practices, recommending that all sources have secondarily traceable air-kerma calibrations and hospital physicists should verify vendor-supplied calibrations for at least a sample (10%) of each source batch, using a calibrated instrument able to support secondarily-traceable calibrations. In this case of HDR ^{192}Ir source calibrations, for which no primary S_K standard exists, the report endorses traceability to an interim secondary standard using an ion chamber with directly traceable ^{137}Cs and orthovoltage external-beam calibration coefficients, allowing a method in which an ^{192}Ir air-kerma calibration coefficient was estimated by interpolation. This approach, first described by Goetsch *et al.*,[45] has become the standard of practice in North America although recent work has shown it has conceptual flaws which fortunately do not lead to large errors.[46]

In 2005, BTSC established a High-Energy Brachytherapy Source Dosimetry (HEBSD) Working Group charged with developing dosimetric prerequisites, a table-lookup formalism and consensus dosimetry data set formation process, and source registry similar to the TG-43-driven infrastructure that exists for low-energy photon emitters. The first HEBSD guidance document was a dosimetric prerequisites[47] document for sources emitting photons with mean energies greater than 50 keV. Like its low-energy counterpart,[41] it recommends secondarily traceable calibrations and a single-source dose distribution derived from two independent dose estimation techniques. For conventionally encapsulated ^{137}Cs and ^{192}Ir sources, the report allows a single (usually Monte Carlo) dose determination method, recognizing that their dosimetry parameters have a predictable dependence on source geometry. Currently, HEBSD is developing a TG-43 like formalism and consensus data sets for common ^{192}Ir and ^{137}Cs sources in conjunction with the ESTRO BRAPHYQS project.

IV.D. Intravascular brachytherapy dosimetry

Due mainly to the foresight of Ravi Nath, the AAPM played an influential role in the brief but dramatic life of intravascular brachytherapy (IVB) through its TG-60 report[48] published in 1999. TG-60 introduced a modified TG-43 dose-calculation formalism, dose reporting criteria, and dose-prescription criteria that were almost universally embraced by the multidisciplinary IVB community. These recommendations influenced the design of clinical trials, the analysis of clinical data, and the direction of dosimetry-related research. Due mainly to the AAPM's contributions to the dosimetry and clinical practice of IVB, the role of the medical physicist was accepted as essential to IVB by both the interventional cardiology and radiation therapy communities.

V. AAPM AND PRIMARY DOSIMETRY STANDARDS LABORATORIES

The National Bureau of Standards (NBS), now the NIST, became involved in the development and dissemination of dosimetry standards for ionizing radiation in 1927 when the Radiological Society of North America (RSNA) urged NBS/NIST to participate in the standardization of x radiation. Since then, NIST has developed a wide range or primary standards related to radiation dosimetry, from free air chambers as air-kerma standards in low-energy x-ray beams, to cavity chambers as air-kerma standards in ^{60}Co beams, to graphite and water calorimeters as absorbed-dose to water standards in ^{60}Co or accelerator beams, and most recently to a WAFAC as an air-kerma strength standard for brachytherapy seeds.

This area of work started with the needs in radiology and radiotherapy as expressed in 1927 by the RSNA. Even today the medical and health-related issues are what motivates the work in developing better primary dosimetry standards around the world. A particularly important fact is that Robert Loevinger, who was among the 12 members of the first Board of Directors of the newly founded AAPM in 1958, became the Head of the Dosimetry Section of the NBS in 1968. In 1970 he proposed the creation of secondary calibration laboratories, directly traceable to the NBS; these became the network of ADCLs of the AAPM. Loevinger was a consummate expert in radiation dosimetry, both experimental and theoretical, and with one foot in the AAPM and one foot in NBS, was able to push the development of graphite-wall cavity-chamber standards for ^{60}Co-beam exposure standards in the 1970s and then in the early 1980s to lead the development of the TG 21 protocol for the determination of absorbed dose from high-energy photon and electron beams, which was based on the new standards.[6]

The connection between the AAPM and the NIST remains extremely close through, among other avenues, the Calibration Laboratory Accreditation Subcommittee that governs the ADCLs. In addition, the Council on Ionizing Radiation Measurements and Standards, created in 1992 to provide recommendations and justifications for primary-standards needs in the U.S., has had a series of illustrious members of the AAPM as officers and chairs of meetings to represent the medical-physics community. In 1996, the President of the AAPM, Bhudatt Paliwal, testified at Federal Oversight hearings and his testimony was passed on to the House of Representatives resulting in "a significant increase in the NIST budget to support their calibration programs."[49]

Although this discussion has focused on the primary standards laboratory of the U.S., the 50 years of AAPM involvement in radiation dosimetry has greatly improved primary standards worldwide through research by its members and by their advocacy at the highest levels in international metrology.

VI. AAPM AND THE ACCREDITED DOSIMETRY CHAIN

As mentioned above, in 1970 the NIST indicated that secondary calibration laboratories could and should be used to provide dosimetry calibrations for end users. Today NIST provides dose and air-kerma calibrations of high-quality instruments submitted by secondary calibration laboratories and a network of these secondary calibration laboratories exists in the United States to provide calibrations of radiation-measuring instruments used in hospitals and clinics.[50] Originally known as Regional Calibration Laboratories, they are now called Accredited Dosimetry Calibration Laboratories (ADCLs). The ADCLs are accredited and supervised by a subcommittee of the Therapy Physics Committee of the AAPM. The role of the laboratories is defined explicitly: They are to obtain several high-quality instruments that have been assigned absorbed dose or air-kerma calibration coefficients by NIST. These instruments become the ADCL's "local standards." They then compare the response of instruments submitted by their customers with those of their local standards, and determine dose or air-kerma calibration coefficients for the customers' instruments, in effect transferring the NIST standard from their own instrument to the customer's instrument. The comparison is conducted in radiation beams that duplicate the NIST beams as closely as possible.[51] Calibrations of instruments for brachytherapy calibrations also are performed, using sources for which NIST has developed air-kerma standards.[52]

The ultimate calibration of the customer's instrument is said to be "NIST traceable," as it is no more than one step removed from NIST. The customer subsequently uses the NIST-traceable instrument to make measurements of dose in a reference material, or of air-kerma strength of brachytherapy sources, and estimate the dose to patients receiving treatment in the hospital or clinic.

The transfer of dose or air-kerma calibration coefficients is to be conducted in a manner which ensures the accurate calibration of the customers' instruments. In 1981, the AAPM developed guidelines for accreditation of the laboratories, and created a mechanism for formal accreditation. These guidelines are maintained and updated by the Subcommittee on Accreditation of Calibration Laboratories. The AAPM Subcommittee subsequently solicited and reviewed applications and conducted site visits which resulted in several ADCLs being accredited by the AAPM. At the moment, there are three ADCLs in operation. The laboratories continue to be monitored by the Subcommittee and must take part in regular round robin tests of their calibration capabilities and pass periodic reviews to maintain their accreditation. The guidelines for accreditation require that a laboratory develop a written protocol which, among other things, requires a statement of laboratory goals for calibration accuracy.

An analysis of calibration laboratory uncertainties was conducted in the late 1990s.[53] While variations were seen among the individual uncertainty values determined by the laboratories, remarkable consistency was seen among their overall results. For example, all of the laboratories indicated an overall uncertainty of less than 1.2% for calibrations of cable-connected chambers in cobalt or x-ray beams of greater than 1 mm Al HVL. It appeared that the differences in data reported by the laboratories were not significant and that a single figure for each class of instrument and beam energy could be adopted.

The AAPM program is unique in many respects, and has served as a model for other laboratory accreditation programs. Few programs have such high expectations for accuracy as the AAPM program and few are as demanding of the traceability to NIST. This is largely because no other accreditation program deals with the delivery of radiation for cancer therapy, where minimizing uncertainties is of paramount importance.

The AAPM continues to supervise the operation of the ADCLs, and is in the process of adapting its operating procedures to become compliant with the requirements of ISO.[54,55] Compliance with international standards has required some restructuring of the AAPM committees supervising the ADCLs, but will enhance the national and international recognition of the AAPM program of laboratory accreditation.

VII. ROLE OF THE RPC IN AUDITING MACHINE CALIBRATION

VII.A. The Radiological Physics Center

The Radiological Physics Center (RPC) was established in 1968 though an agreement between the AAPM and the Committee for Radiation Therapy Studies (CRTS), a committee of the NCI. CRTS had recognized a need for consistent dosimetry and QA in the NCI's clinical trials program and approached the AAPM in 1967 with the request that AAPM seek proposals to establish a center that would monitor the radiation therapy facilities that participate in NCI clinical trials. Four proposals were received and the proposal

from The University of Texas M. D. Anderson Cancer Center in Houston, submitted by Robert Shalek, was accepted.

As defined by Shalek's proposal, the role of the RPC was to assure NCI and the cooperative groups that participating institutions deliver comparable and consistent doses, and that the institutions have no serious deficiencies in their quality assurance programs. The RPC, still located at M. D. Anderson, has functioned continuously since September of 1968. The RPC continues to enjoy a close relationship with the AAPM. The AAPM's Therapy Physics Committee (TPC) functions as the RPC's Technical Advisory Committee, and meets at the RPC's offices in Houston each spring. The RPC attends all TPC meetings and reports on its activities, new initiatives, finances, and grant status. The AAPM provides a link to the RPC's website[58] and permits the RPC to send occasional email bursts to AAPM members, announcing new findings and clinical trial issues of interest.

The RPC also maintains a Clinical Advisory Committee consisting of five senior radiation oncologists who are active in clinical trials and are familiar with the QA requirements. The Clinical Advisory Committee meets when circumstances and finances permit.

VII.B. RPC QA monitoring activities

The RPC is presently monitoring 1532 radiation therapy facilities. Most of these are in the United States, 30 are in Canada, and another 24 are located elsewhere in the world. The RPC will soon add another 30 European institutions through an agreement between the RPC, NCI, and the European Organization for Research and Treatment of Cancer.

The RPC's monitoring activities include remote audits, on-site dosimetry reviews, credentialing for specific clinical trials, and patient record reviews. Because this article addresses radiation dosimetry, this section will focus on the RPC's remote and on-site audits of treatment machine calibration.

One of the RPC's most important and most visible programs is remote audits which provide the regular measurement of treatment machine output using mailed TLDs.[56] The purpose of this program is to assure consistency of patient doses at participating institutions, to help the RPC prioritize institutions for dosimetry review visits, to help satisfy state or local requirements for an independent audit of radiation therapy facilities and to provide a model for other monitoring programs.

The monitoring program makes use of "standard" TLDs irradiated on a cobalt unit under carefully controlled conditions. The cobalt unit is calibrated using the TG-51 protocol, with a NIST-traceable instrument calibrated at the M. D. Anderson ADCL, thereby assuring traceability to NIST.

To meet the RPC's criteria for agreement, the TLD's reading must agree with the institution's stated dose within 5%, and electron depth dose curves must correspond to within 5 mm. This 5% figure was chosen based on an analysis of the uncertainty of the RPC's TLD measurements which showed that 5% represents the 93% confidence limit.[57]

During 2006, the RPC measured just over 13 000 beams at 1480 institutions. Of these measurements, 751, or about 5.8% fell outside the RPC's 5% criterion. A number of these discrepant results were attributed to gross errors such as setting 100 monitor units when 300 were intended, or irradiating the TLD with the wrong beam energy. When these errors were excluded, approximately 1.2% of all photon beam TLD measurements fell outside the RPC's 5% criterion, while for electrons, the rate was 2.3%. However, the discrepant results were distributed among the monitored institutions, so that roughly 11% of monitored institutions had at least one beam that fell outside the RPC's criteria. This trend has been maintained over the last 5 years. However, the current results reflect an improvement over data collected in the early 1990s when Kirby *et al.* reported that 4.2% of photon beam measurements, and 7.5% of electron beam measurements fell outside the RPC's 5% criterion.[57]

If a result is outside the RPC criteria, an RPC physicist calls the institution's physicist to discuss the results and examine possible causes of the discrepancy. In some cases, the institution sends calibration records for review by the RPC. If the discrepancy cannot be explained, a repeat TLD is sent to confirm the result.

The RPC is almost always able to help the institution discover the causes of TLD readings that fall outside the criteria for acceptability.

VII.C. On-site dosimetry review visits

Another important RPC program that addresses machine calibration is the program of on-site dosimetry review visits. Visits are conducted at the rate of approximately 40–50 institutions per year. Institutions are selected for visits based on criteria that include the number of patients registered on clinical trials, the number and type of treatment machines in use, the variability of annual RPC TLD measurements, and the time elapsed since the previous RPC visit, if any. In addition, TLD measurements that fall outside the RPC criteria and that cannot be explained or resolved by remote means will move the institution to high priority for a visit. Similarly, an inability of the RPC to come to agreement with the institution over the dosimetry of a patient treatment record or evidence of a lapse in the institution's QA program will move the institution to higher priority.

The dosimetry review visit includes a measurement of basic beam calibration, as well as investigation of output factors, transmission factors, depth dose values, and specific measurements of multileaf collimators and independent jaws. The RPC has established a threshold of 3% for agreement of an ionization chamber measurement with the institution's output calibration. More than 25% of the institutions visited since 2001 were found to have at least one radiation beam that exceeded 3% difference with the RPC measurements. In almost all cases, the cause of the discrepancy was traced to errors in application of the calibration protocol, the use of inaccurately characterized plastic phantom material, or the use of instruments for which dosimetry parameters have not been defined by the calibration protocol in use. In nearly

every case, the discrepancies were confirmed by the institutions once corrections were made for the deficiencies discovered during the visit.

VIII. CONCLUSIONS

Throughout its history, the AAPM has recognized the central role of radiation dosimetry in the accurate delivery of radiation therapy. As a result of this recognition, the AAPM has played a major role in clinical dosimetry, from encouraging research, to developing protocols for various types of radiation sources, to arguing for strong government support for primary standards laboratories, to accrediting ADCL's and supporting the RPC's role in quality assurance. This is an enviable record for the organization and one of the major reasons for its success over its first 50 years. While it is clear that dosimetry is no longer a "hot topic" for the general membership, in part due to the significant successes of the past, radiation dosimetry will continue to play a central role in radiotherapy and, hence, an important role in the AAPM in its next 50 years.

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