Report of the NIST Dosimetry Group to CCRI Section I

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This report is intended to be an overview of the activities of the Dosimetry Group at the National Institute of Standards and Technology (NIST) for the meeting of Section I (x and gamma rays, charged particles) of the Consultative Committee on Ionizing Radiation (CCRI), March 26-28, 2013. Since the last meeting of CCRI(I), a reorganization of the Ionizing Radiation Division has taken place, whereby it has been renamed the Radiation and Biomolecular Physics Division and is comprised of three groups: Dosimetry, Radioactivity, and Neutron Physics. The function of the re-named Dosimetry Group (formerly the Radiation Interactions and Dosimetry Group) remains unchanged.

Technical highlights

- New NIST reference mammography beams using a tungsten target and silver, rhodium, molybdenum and aluminum filters at 20 kV to 50 kV have been developed. These beams will provide FDA inspectors, ionization chamber manufacturers, and calibration facilities with the techniques that best represent what is used in clinics. These new reference radiation techniques will be available for calibrations and the FDA-MQSA proficiency tests. The NIST 100 kV tungsten anode x-ray unit and the Ritz primary standard free-air ionization chamber are being used for the digital mammography techniques. Air-attenuation corrections have been measured directly, and other correction factors have been calculated with Monte Carlo methods using measured beam energy spectra. Correction factors will be determined for various anode/filter combinations, including W/Ag, W/Rh, W/Mo and W/Al, with and without 2 mm Al additional filtration, in 5 kV increments between 20 kV and 50 kV. Upon final determination of the corrections, the air kerma will be realized, allowing for an indirect comparison with another NMI that supports these reference radiations.
- In an effort to both reduce and improve the monitoring of radiation dose delivered to patients during computed tomography (CT) procedures, the NIST has an ongoing project that involves the characterization of clinical dosimeters and reference quality ionization chambers. The goal of this project is to provide guidelines to users of these instruments for performing QA checks. The project involves use of the x-ray beam calibration facility and NIST PET/CT unit, as well as other medical/research CT facilities. Multiple CT chambers are being calibrated to determine their energy dependence and the applicability of the current reference radiation techniques dedicated for CT use. The chamber response will be used to determine the NIST proficiency test parameters for CT, including uncertainty expectations. The CT

chamber data will serve as a foundation for the evaluation of the transfer of currently used reference radiation techniques for air-kerma calibration coefficients to medical CT units. Dose measurements are being performed using radiochromic film and OSL dosimeters.

- The NIST has developed a new facility for the calibration of the Xoft miniature x-ray source, which provides low-energy x-rays (< 50 keV) for electronic brachytherapy applications. A reference air-kerma rate of the sources has been directly realized through use of the Lamperti free-air chamber. The Lamperti chamber has a history of direct traceability at the BIPM and is designed for the energy range required in electronic brachytherapy. The energy spectrum from individual sources is measured using a high-purity germanium (HPGe) spectrometer, which is mounted opposite the free-air chamber to allow simultaneous measurement of the air-kerma rate and tube output spectrum. The spectral information has been used to determine correction factors for the Lamperti chamber. Comparison measurements between the Ritz and Lamperti primary standard chambers were conducted, and the Lamperti chamber was also compared to the Attix chamber using the rhodium x-ray tube in an effort to further investigate the direct determination of air attenuation corrections. A measurement comparison with the University of Wisconsin began in January 2013, where four electronic brachytherapy sources were evaluated using the Lamperti primary free-air ionization chamber and two well chambers. The NIST determined the air kerma rate for each source at a distance of 50 cm using the Lamperti chamber. The well chambers are used to measure the stability of the source output and serve as transfer instruments.
- The NIST is pursuing a program of x-ray spectroscopy of highly-charged ions and plasmas using custom-designed and constructed curved crystal spectrometers. X-ray sources of interest include the Electron Beam Ion Trap (EBIT), Electron Cyclotron Resonance Ion Source (ECRIS), and laser-produced plasma ion sources, including the new generation of petawatt lasers. In support of these efforts, we also maintain laboratory x-ray sources from 1 keV to 300 keV, energy and intensity calibration facilities, and a vacuum double-crystal spectrometer for precision wavelength measurements tied to the definition of the meter. In addition to both applied and fundamental data and processes, emphasis is placed on advanced and novel instrument development, precision metrology, and techniques of calibration.
- The Photon and Charged Particle Data Center has long been an international source of photon and charged particle reference data that have been used in stand-alone applications or integrated into transport codes to solve problems in radiation physics. Another function of the Center has been to evaluate computer codes, to modify them when necessary, and to use them to solve problems in support of dosimetry projects at the NIST. The focus of the Center in recent years has been 1) to address the issue of uncertainty in some of the Center’s databases, 2) to investigate the integration of some nuclear physics into the Center’s databases (photonuclear cross sections) and Monte Carlo capabilities (proton transport), and 3) to provide reference data and publications for some of the Dosimetry Group’s radiation sources. Maintaining the Center is critical to avoid knowledge gaps that would make it impossible to completely specify the uncertainty in standards and protocols.

- Absorbed dose to water is a quantity crucial to radiation therapy for cancer treatment, and water calorimetry, based on Domen's work, is increasingly the basis for NMI primary standards for this quantity worldwide. For dosimetry of high-energy photon beams from both Co-60 and MV x rays, experimental and computational studies of the heat defect due to radiolytic reactions involving water impurities is being carried out at the NIST. The official commissioning of a revised primary standard for Co-60 and a new primary standard for MV x rays is anticipated in the near future.
- Using ultrasonic thermometry to measure absorbed dose to water from ionizing radiation was first demonstrated at the NIST a few years ago. In that work, a single contact transducer was used to measure small, temperature-induced changes in the speed of sound within an irradiated volume of water. Since then, preliminary experiments involving a circular ultrasonic array have been used to image 2D temperature distributions in water due to radiation from a heat lamp. A detailed study of both the thermal and spatial resolution of the 2D ultrasonic array is being carried out to examine the feasibility of noise-correlation techniques to enable multi-source/receiver signal acquisition. The system has been used to image spatially complicated heat sources from infrared radiators and power-resistor configurations, as well as the electron beam from the NIST Van de Graaff accelerator. The system has also been tested in high-energy x-ray beams from the Clinac 2100C to demonstrate its suitability for radiation therapy applications. The detection principle employed in the ultrasonic array exploits temperature dependence in the speed of sound to measure small changes in time-of-flight of ultrasonic pulses. Such phenomena are also suitable for detection by highly sensitive interferometric means, and this is being explored with both ultrasonic and optical probe radiations. A short study conducted last summer with a student intern verified much higher thermal sensitivity of optical interferometry (as compared to ultrasonic interferometry), thereby motivating further work on developing an imaging instrument that would use an optical probe for ultra-high sensitivity thermometry suitable for radiation dosimetry.
- The NIST recently participated in an intercomparison involving US proton therapy clinics. Energetic protons used in conformal radiotherapy exhibit little side scatter when injected into human tissue and deposit most of their energy within a small volume as they come to rest, sparing surrounding healthy tissue while targeting cancerous tumors. The need for measurement traceability for radiation dosimetry has been receiving greater attention at proton clinics as part of the quality assurance programs that assure therapeutic efficacy and patient safety. An initiative launched recently by the National Institutes of Health's National Cancer Institute (NCI) and Massachusetts General Hospital to establish NIST traceability and to investigate measurement consistency among existing dosimetry protocols (ICRU 59 and IAEA TRS-398) led to the participation of the NIST in an intercomparison conducted at the Proton Therapy Center, MD Anderson Cancer Center (MDACC) in Houston, Texas in late 2011. Altogether, representatives from nine different US clinical proton facilities, the Radiological Physics Center at MDACC and the NIST brought pairs of reference quality ionization chambers, one thimble and one plane-parallel, to carry out measurements under identical conditions in two different proton treatment settings, chosen to simulate brain and prostate irradiation conditions. More recently, the NIST brought both chambers and the water calorimeter to one of the proton

facilities involved in the intercomparison (Hampton University Proton Therapy Institute, in Hampton, VA) and conducted measurements in a similar proton beam.

- In response to recent requirements for the widespread security screening of baggage, cargo, and airline passengers, the NIST is working on new national and international standards, test methods, test artifacts, dosimetry protocols and technical guidance documents, supported by an infrastructure of R&D, field testing, radiation metrology and computational modeling. The primary objective of this project is to assure the technical performance and radiation safety of x-ray and gamma-ray security screening systems in all venues in which they are deployed in order to fill the well-documented gaps in transportation and commercial security. The performance standards call out test artifacts, test methods, and, in some cases, required minimum performance levels; they do not address threat detection performance directly. All imaging modalities are treated: transmission and backscatter geometries as well as computed tomography (CT). The goal is to insure the safe use of these technologies and to provide governmental users and industrial partners with standard gauges to compare technical aspects of performance and that will also stimulate and quantify future technological advances.
- Advanced (and some conventional) cargo-inspection systems employ high-energy x-ray beams from accelerators (above 5 MV). Currently, air-kerma measurements at these high energies are not directly traceable to national standards. Recommendations for the radiation protection of possible exposed occupants require in-beam measurements that would be better justified if properly traceable to national standards. A small, brass-walled ionization chamber was designed and built at the NIST to directly realize air kerma in such beams. Characterization and quality assurance testing of the brass standard ionization chamber is carried out using MV photon fields from the Clinac accelerator at the NIST. Various corrections that need to be applied to the standard are being evaluated using both Monte Carlo and measurement methods.
- Enhanced x-ray image acquisition and analysis methods that are applicable to, for example, security and medical applications of x-ray imaging as well as basic science techniques such as wavelength-dispersive spectroscopy are being studied. A variety of in-house x-ray sources and detector technologies invite efforts to optimize traditional image quality metrics and the use of algorithms and methods to extract the maximum amount of information available. These results are used to inform x-ray standards development and will drive the technical performance of future commercial x-ray imaging systems.
- The NIST has an ongoing program in small-field therapy dosimetry studies using alanine/EPR. An international protocol is under development by the IAEA and the AAPM to address the difficult problems of small-field dosimetry in radiation therapy (e.g., GammaKnife, IMRT, Cyber Knife, TomoTherapy), encountered when going from national standards in large reference fields to small fields, through the use of alanine/EPR dosimetry. The NIST currently provides measurement support for an ongoing survey of approximately 100 Leksell Gamma Knife (LGK) units worldwide in collaboration with the University of Pittsburgh Cancer Center, and is planning (1) the use of smaller alanine pellets to address smaller fields, and (2) the increase in sensitivity by appropriate use of EPR signal-generating reference material and more

complex signal-analysis software. If successful, the use of small alanine pellets to characterize radiation treatment fields would significantly improve both the spatial resolution and accuracy of clinical dosimetry.

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Comparisons Done in 2011-2013

- BIPM.RI(I)-K1 (Co-60 air kerma): Published in *Metrologia* in 2013.
- BIPM.RI(I)-K2 (low energy x ray air kerma): Published in *Metrologia* in 2012.
- SIM.RI(I)-K3 (SIM Comparison of Calibration Coefficients at Radiotherapy Level for Orthovoltage X-ray Beams – NIST, NRCC, ININ, CNEA and LNMRI); SIM.RI(I)-K3.1 (NIST and KREB): Reports in progress, Draft A.
- BIPM.RI(I)-K5 (Cs-137 air kerma): Report in preparation.
- BIPM.RI(I)-K6 (absorbed dose to water from linac high-energy photon beams): Report in progress, Draft B.
- BIPM.RI(I)-K7 (mammography x ray air kerma): Published in *Metrologia* in 2011.
- CCRI(I)-S2 (Co-60 absorbed dose to water for radiation processing, 1 kGy to 30 kGy): Published in *Metrologia* in 2011.

Future Comparisons

- BIPM.RI(I)-K4 (Co-60 absorbed dose to water): Comparison is planned for late 2014.
- BIPM.RI(I)-K8 (Ir-192 HDR, I-125 LDR brachytherapy air kerma): The University of Wisconsin will participate in the high-dose-rate Ir-192 part of the ongoing comparison on the NIST's behalf. The NIST will participate in the low-dose-rate I-125 part of the comparison.

Facility upgrades

- The design and construction of a new Cs-137 gamma-ray beam calibration facility has been completed, extending the range of air kerma rates currently available at the NIST. The new facility includes an irradiator, a detector positioning system, and safety indicators and controls. It features a large number of design innovations compared to calibration ranges currently available, resulting in a significant increase in measurement reproducibility.
- Design of the Applied Irradiation Manufacturing Standards (AIMS) facility is in progress. A 10 MeV, 17 kW accelerator will be part of an electron beam processing dosimetry test bed to enable traceability to national standards for industrial irradiation applications.
- An HDR brachytherapy source calibration facility is planned.