Recent Dosimetry Activities at the NIST

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1. INTRODUCTION

The following is intended as a general overview of activities by the Radiation Interaction and Dosimetry Group, Ionizing Radiation Division, National Institute of Standards and Technology (NIST), USA, for the meeting of Section I (X and γ rays, electrons) of the Consultative Committee on Ionizing Radiation (CCRI), May 13-15, 2009, Paris. The material was taken from information gathered for NIST program reviews, and covers roughly calendar years 2007 and 2008. Our technical activities are summarized in Section 2, identifying staff members involved in each project; Section 3 lists the Group's publications for the period, and Section 4 lists the talks given.

I'm sad to report that Paul Lamperti died on February 4, 2009, from pancreatic cancer. Paul was for decades a key contributor in air-kerma standards for x-ray and gamma-ray beams, and in their dissemination. Paul retired from NIST about five years ago, but continued to be a important technical resource for our programs. He was long a colleague and friend, both to me and to many of our staff; he will be missed.

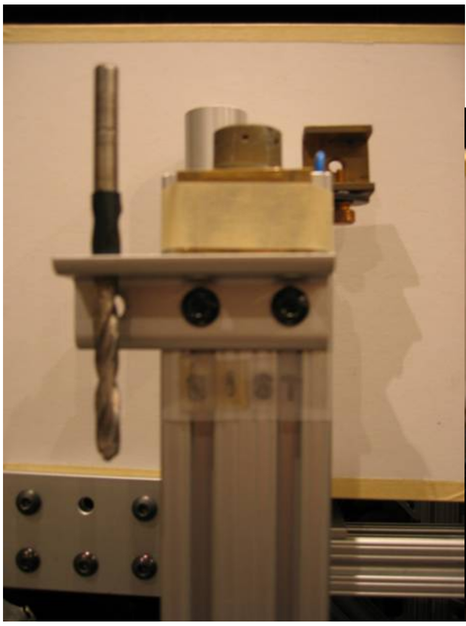
2. TECHNICAL ACTIVITIES

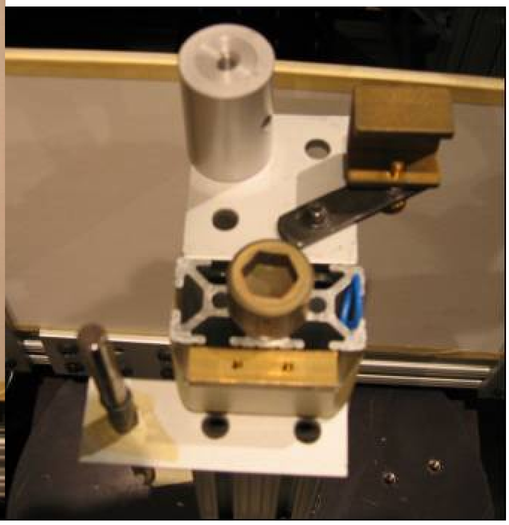
A. Facilities and Radiation Physics

Accelerator Facilities

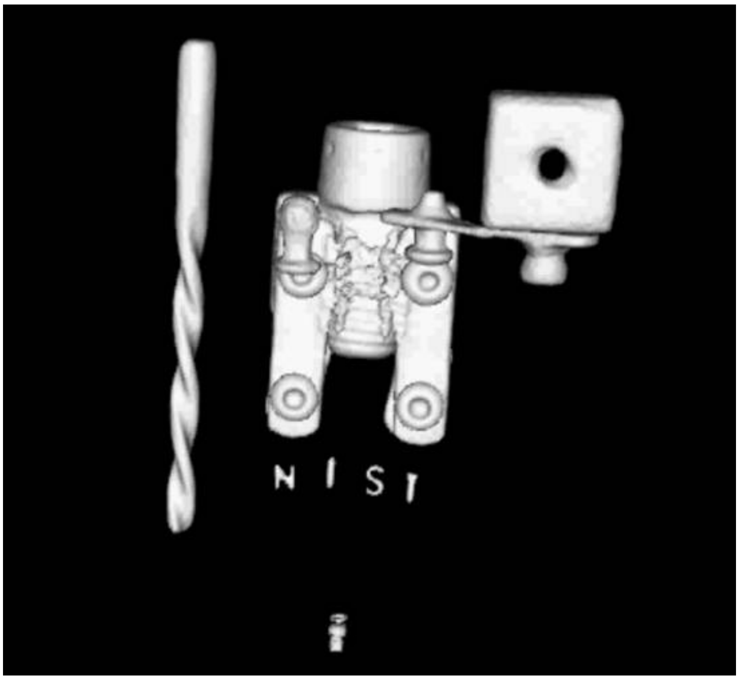
The Division's accelerator facilities continue to support research efforts in industrial and medical dosimetry, homeland security, and radiation-hardness and materials-effects studies. During this reporting period, our facilities were utilized by a diverse group of internal and external users representing private industry, government, and academia. Topics of research included: irradiation of polyethylene samples to improve their efficacy in medical prosthetics, calibration of charged-particle spectrometers used in space-flight and fundamental physics applications, characterization of graphite and water calorimeters, and a study of the radiation resistance of diodes used in radiation survey instruments.

During the past two years significant progress was made toward the development of the Division's High-Energy Computed Tomography (HECT) imaging system. Working with increasingly complex test objects, we were able to better gauge system performance and improve our image reconstruction techniques. A series of electron beam collimators have been fabricated which will allow us to determine the effect of the beam spot size on the quality of the reconstructed images, and software tools have been developed to allow three-dimensional isosurface renderings of the HECT image data (see figures below).





Photograph of HECT test object (side view). Photograph of HECT test object (top view).



Iso-surface rendering of reconstructed HECT test object data.

We have also made considerable progress in the area of industrial dosimetry. Over the past several months we have designed, fabricated and begun testing a new graphite calorimeter intended for use in high-energy, high-dose rate electron beams such as those used in radiation processing. Tests of the calorimeter were performed using 12 MeV beams from the Clinac accelerator, at a source-to-surface distance of 100 cm with a field size of 10 cm x 10 cm. As a check of the calorimeter response, a graphite phantom was constructed, and a plane-parallel ionization chamber placed at the same depth as the center of the calorimeter core. Doses obtained from the ionization chamber measurements, taken under identical conditions, agreed with the calorimeter results to within 0.6 %.

In the area of medical dosimetry, the Clinac accelerator was used extensively to validate the performance of a water calorimeter which will serve as the new national standard for high-energy X-rays. These data are currently being analyzed. Once the performance of this calorimeter has been properly validated, the Clinac facility will serve as a high-energy calibration laboratory based on this primary dosimetry standard.

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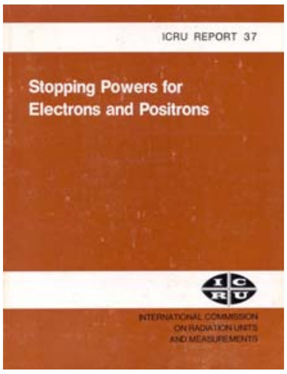
Standard Reference Data on Radiation Interactions

NIST has nearly five decades experience in the development of critically evaluated, comprehensive databases of cross-section information for ionizing photons (x and gamma rays), electrons, and heavy charged particles. These data are often adopted by national and international standards organizations for use in radiation protection, medical therapy, and industrial applications. This work continues in the Division's Photon and Charged-Particle Data Center. The quality of the work of the Data Center is reflected in the many requests for our data from other laboratories and in the use of our data in engineering and scientific compendia, books and review articles, and in the reports and protocols of national and international standards organizations. Each year we respond to more than a hundred inquiries from the medical, industrial, academic, government, and other scientific communities for technical information and data. The compilations of the Data Center rely heavily on the synthesis of available theory to extend the data and provide for comprehensive coverage over broad ranges of energy and materials. Thus we have long been involved in complex computational analyses and in the development of highly sophisticated transport-theoretic methods. Our Monte Carlo transport calculations also are incorporated into some of the most widely used general-purpose radiation transport codes. With the help of the NIST Physics Laboratory's Office of Electronic Commerce of Scientific and Engineering Data, a number of the Center's databases can be accessed on the worldwide web.



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Theoretical Dosimetry and Radiation-Transport Calculations

The radiation transport and Monte Carlo methods pioneered and developed at NIST to calculate the penetration of electrons and photons in matter are used in most of the major codes today. Monte Carlo simulation is increasingly applied to problems in radiation metrology, protection, therapy and processing as an accurate tool for design, optimization and insight often inaccessible to measurement. Our programs continue to develop and use Monte Carlo calculations for the understanding and refinement of our measurement standards, and for the many applications of ionizing radiation with which we are involved.

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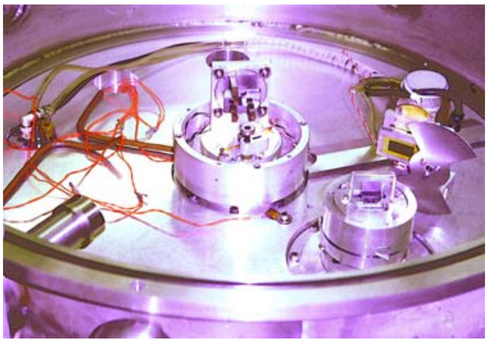
Low-Energy Absolute X-Ray Wavelength Metrology

A vacuum double crystal spectrometer (VDCS) is being used to generate absolute x-ray reference wavelengths from 1.2 nm to 0.1 nm (1 keV to 12 keV), traceable to the definition of the meter, at the femtometer level of accuracy and precision. To accomplish such, this instrument operates in the Advanced Measurement Laboratory in a custom-designed environment with extreme temperature and vibration stability. This instrument performs precision x-ray wavelength measurements in support of high-accuracy transfer standards needed in fundamental experiments at NIST and around the world. In many cases, the error budget of such experiments is limited by the CRC (Bearden) wavelength tables. The results will also complement NIST's new x-ray wavelength tables project by making modern measurements of transition energies that differ significantly from the most recent theoretical calculations. The project has produced novel calibration techniques for angle encoding (at the 0.02 arc second level), new methods and techniques for in-vacuum alignment of the x-ray crystal optics, and new formalism for quantifying the correction of the apparent diffraction angle due to system misalignments. In addition to wavelength metrology, the VDCS will also perform the first direct measurements of the index of refraction in silicon using an innovative approach.


The NIST vacuum double-crystal spectrometer

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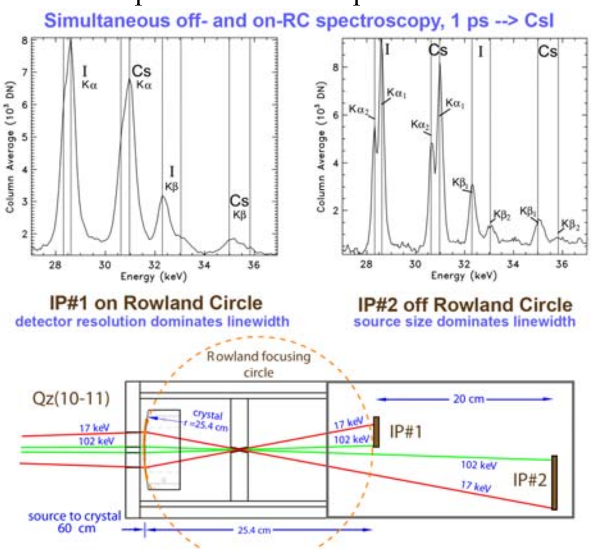
Applications of Diagnostic X-Ray Spectrometers

We continue to design, produce, and calibrate bent-crystal diagnostic spectrometers for customers around the world. These have been fielded to help characterize the performance and x-ray spectra from advanced medical x-ray sources, laser-produced plasmas, terawatt pulsed accelerators, electron cyclotron resonance ion sources, electron beam ion traps, intense ultrafast laser sources, and inverse-Compton backscatter sources. Recently a theory of enhanced x-ray resolving power achieved behind the Rowland (focusing) Circle (RC) of Cauchois spectrometers was developed and demonstrated at the Ecole Polytechnique-Universite Laboratoire pour l'Utilisation des Lasers Intenses (Paris). With a single picosecond laser pulse, K-shell x rays from a CsI target were simultaneously registered both on and off the focal circle (shown in picture). This formalism can be used to measure source-size broadening in a variety of x-ray radiography applications.



Optical design and instrumental resolving power as a function of source size and detector position

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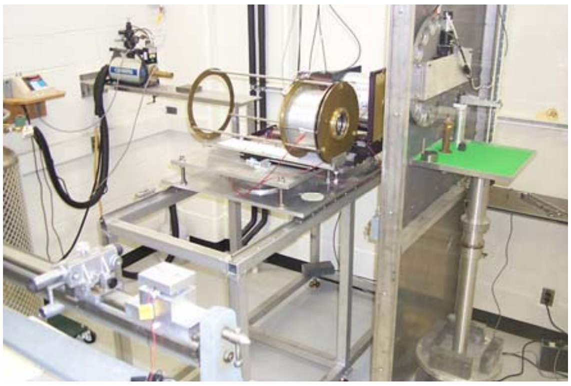
B. Medical Radiation Dosimetry

Calibration of Low-Energy Photon Brachytherapy Sources

Small radioactive "seed" sources used in prostate brachytherapy, containing the radionuclide ^{103}Pd, ^{125}I, or ^{131}Cs, are calibrated in terms of air kerma strength using the NIST Wide-Angle Free-Air Chamber (WAFAC). The WAFAC is an automated, free-air ionization chamber with a variable volume, allowing corrections to be made for passage of the beam through non-air-equivalent electrodes. In the past nine years, about 900 seeds of 40 different designs from 18 manufacturers have been calibrated using the WAFAC.



On-site characterization at seed manufacturing plants for quality control, as well as at therapy clinics for treatment planning, relies on well-ionization chamber measurements. Following the primary standard measurement of air-kerma strength, the responses of several well-ionization chambers to the various seed sources are determined. The ratio of air-kerma strength to well-chamber response yields a calibration coefficient for the well-ionization chamber for a given seed type. Such calibration coefficients enable well-ionization chambers to be employed at therapy clinics for verification of seed air-kerma strength, which is used to calculate dose rates to ensure effective treatment planning. To understand the relationship between well-ionization chamber response and WAFAC-measured air-kerma strength for prostate brachytherapy seeds, emergent x-ray spectra are measured with a high-purity germanium (HPGe) spectrometer. Knowledge of seed spectra allows separation of well-ionization chamber response effects due to spectrum differences from those due to seed internal structure and self-absorption, which influence the anisotropy of x-ray emissions from the seed. The relative response of calibration instruments has been observed to depend on such anisotropy.

Seed manufacturers periodically send batches of three to five seeds to NIST for calibration. These seeds are then forwarded to several Accredited Dosimetry Calibration Laboratories (ADCLs) to establish and subsequently maintain the secondary standard at these laboratories for use in calibrating clinical well-ionization chambers. To ensure that seeds submitted for WAFAC calibration are consistent and representative of that particular seed design so that associated errors will not be propagated down the traceability chain to the ADCLs, seed manufacturers, and therapy clinics, several additional tests have been implemented. The distribution of radioactive material within a seed is mapped using radiochromic film contact exposures. The in-air anisotropy of seeds is studied by taking WAFAC and x-ray spectrometry measurements at discrete rotation angles about the long axis and the axis perpendicular to the mid-point of the long axis of the seed, respectively. The "air-anisotropy ratio", calculated from the results of angular x-ray measurements, has proven to be a useful parameter for explaining differences in well-chamber response observed for different seed models having the same emergent spectrum on their transverse axis.

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Evaluation of Uncertainty in Brachytherapy Dosimetry

NIST is participating in Task Group # 138 (TG-138) of the American Association of Physicists in Medicine (AAPM), "AAPM Recommendations on Assessing Uncertainty of the Brachytherapy Clinical Dose Evaluation Process." The goal of TG-138 is to assess the birth-to-death process of brachytherapy source manufacture, dosimetry, calibrations, treatment planning, and clinical implementation for identifying most all sources of uncertainty towards quantifying realistic clinical evaluation of treatments. NIST is in a unique position to contribute to this effort by analyzing ionization chamber, anisotropy, and x-ray spectrometry data collected on hundreds of prostate brachytherapy seeds over the past several years. Sources of uncertainty that influence the chain of traceability of the NIST primary air-kerma strength standard to the clinics via secondary calibration laboratories will be identified and quantified, including those due to batch-to-batch variability of the physical properties of seeds.

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Calibrations of a Miniature X-Ray Source Used for Electronic Brachytherapy

Setup of a new laboratory dedicated to establishing a national primary air-kerma rate standard for Xoft's AXXENT™ miniature x-ray source is in progress. The Xoft source was designed to provide low-energy x-rays (< 50 keV) for use in brachytherapy. Air-kerma rate will be directly realized through use of the Lamperti free-air chamber. A high-purity germanium (HPGe) x-ray spectrometer will be used to monitor the energy spectrum of the beam in real time, as well as provide necessary input data for Monte Carlo calculations of correction factors for the free-air chamber. To account for spatial anisotropy of emissions, the free-air chamber and spectrometer will be rotated about the long axis of the x-ray tube during measurements. The response of well-ionization chambers to the x-ray sources will be studied in preparation for the development of a measurement assurance program for the dissemination of the new NIST standard to Accredited Dosimetry Calibration Laboratories (ADCLs). The ADCLs are accredited by the American Association of Physicists in Medicine (AAPM), and calibrate radiation measuring instruments for use in therapy clinics.

Xoft AXXENT™ electronic brachytherapy unit under test

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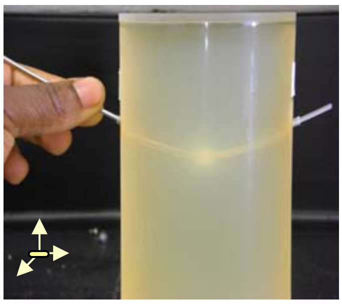
Polymer Gel Dosimetry with High-Resolution Optical Computed Tomography

An innovative polymer gel scanning system has been developed by MGS Research, Inc., Madison, CT and is being used at NIST for high resolution three-dimensional (3D) dose distribution measurements. The system is capable of voxel resolutions of 0.1 mm in all dimensions and has been used to measure dose distributions from photon and beta particle brachytherapy sources. A special very small field (1 cm × 1 cm) ^{60}Co gamma ray beam has been characterized for gel calibrations, and measurements are planned for still more challenging sources, such as concave ophthalmic applicators.



Results of gel measurements are being compared with measurements using small-volume ionization chambers, micro-scintillators, radiochromic film, and thin thermoluminescence dosimeters (TLDs). All of the latter are performed in a specially designed water phantom with the detectors either in water or covered with minimal layers of water-equivalent plastic.

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Beta-Particle-Emitting Ophthalmic Applicator Calibration Service

The NIST primary standard for beta-particle brachytherapy sources relies on extrapolation-chamber measurements, but quoted uncertainties are unacceptably high (>10 % at 2σ), mainly because of curvature of the current vs. air gap function, which leads to uncertainty in the measured absorbed-dose rate. Recent calculations have shown that this curvature can largely be removed through the application of a divergence correction to account for ionization losses at finite air gaps associated with the geometry of the source and extrapolation chamber. The divergence corrections were calculated using various Monte Carlo codes; most of the calculations used to determine the correction were done with EGSnrc Version 3. Air gaps between 0.01 mm and 0.5 mm were modeled, as well as three collecting-electrode materials: carbon, water, and D400 conducting plastic. Collecting-electrode diameters between 1 mm and 8 mm were modeled, and for each of these collecting-electrode/air-gap combinations three ^{90}Sr/Y beta-particle source geometries were modeled: a 1 cm diameter ophthalmic applicator, and 0.56 mm and 2.3 mm diameter seeds placed at a depth of 2 mm in water. The corrections are now being applied to all measurements since 1 January 2003. They are also being applied to prior measurements to assess the changes associated with the curvature in the current vs. air-gap function. An additional outcome of these investigations is a revised value for the electrode backscatter correction. Initial findings indicate the use of the new corrections will result in dose rates of ophthalmic applicators being increased by approximately 6.5 %. As a result of these calculations, the NIST uncertainty budget for these calibrations has been revised, and the expanded (k=2) uncertainty has been reduced from 12 % to 7 %.

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X-Ray Calibration Range Measurements

The calibration and irradiation of instruments that measure x-rays are performed in the NIST x-ray calibration facilities in terms of the physical quantity air kerma. Calibrations are performed by comparing the instrument to a NIST primary standard, which include four free-air chambers. Air-kerma-measurement comparisons with the BIPM and other primary standards laboratories are conducted for quality assurance. One important comparison has been made of the air-kerma standards for low-energy x-rays at the NIST and the Physikalisch-Technische Bundesanstalt (PTB). The comparison involved a series of measurements at the PTB and the NIST using the air-kerma standards and two NIST reference-class transfer ionization chamber standards. This indirect comparison with PTB will be the third comparison for mammography energies, but the first for NIST using the recently developed BIPM/CCRI reference beam qualities. The results of the CCRI beam comparison will verify the new correction factors implemented for those techniques for the NIST standard, prior to the next direct BIPM comparison.

Air-kerma calibration coefficients were compared at the radiotherapy level for orthovoltage x-ray beams for members of the Sistema Interamericano de Metrología (SIM). Five SIM laboratories participated in the comparison: NIST, NRCC, ININ, CNEA and LNMRI. Results from the comparison will meet requirements of the Mutual Recognition Arrangement (MRA) and support several CMCs (calibration and measurement capability claims) for NIST and our colleagues. The NIST has served as pilot laboratory for this comparison. The results reveal the degree to which the participating calibration facility can demonstrate proficiency in transferring air-kerma calibrations under the conditions of the said facility at the time of the measurements.

Air-kerma calibration coefficients are currently being compared for narrow x-ray spectra and for cesium-137 between the NIST and the Kenya Bureau of Standards (KEBS). A NIST reference-class transfer ionization chamber will be calibrated by each laboratory in terms of the quantity air kerma for four tungsten-anode reference radiation qualities of energies between 80 kV and 150 kV and for Cs-137 gamma rays.

In addition to participating in measurement comparisons, the NIST x-ray facilities are used to conduct proficiency tests for various NIST customers. NIST customers, which include secondary-calibration facilities, chamber manufacturers, nuclear industry, Department of Energy, Department of Defense, private calibration facilities, medical facilities and the Food and Drug Administration, request calibrations in terms of Gy/C for various reference-quality ionization chambers to achieve traceability to NIST.

The molybdenum anode tube has been replaced in the NIST Mammography Calibration Facility. All Mo anode beams are currently being characterized. The previous half-value layers will be maintained for reference techniques. The kV will be calibrated using the NIST traceable voltage dividers. The air attenuation coefficients will be re-determined. New computers and data acquisition systems will be installed in both x-ray calibration facilities. New thermometers and a new barometer will be installed in the 100/300 calibration range to replace the existing analog models.

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The Development of New Reference Standards for Digital Mammography

With the introduction and FDA approval of mammography units using a tungsten (W) anode with either a silver (Ag) or rhodium (Rh) filter, there are new concerns about air kerma, dose and non-invasive kVp measurements. The response of ionization chambers in the 20-40 kV mammography energy range is relatively flat. However, the FDA is concerned if a solid-state air-kerma measuring device is used that is not calibrated in the appropriate energy spectrum, dose errors will result. The new NIST reference mammography beams using a tungsten target and silver, rhodium, molybdenum (Mo) and aluminum (Al) filters at 20 kV to 50 kV will provide FDA inspectors, chamber manufacturers and calibration facilities with the techniques that best represent beams used in the clinics. It may be possible in the near future for NIST to provide kV measurements for the non-invasive kV meters which are commonly used to measure the kV and HVL on clinical units. These new reference standards will be available for calibrations and the FDA-MQSA proficiency tests. The 100 kV x-ray unit will be used for all the new techniques. The kV has been fully calibrated using the NIST traceable voltage dividers. The beam parameters will be the same as those techniques supported by the German standards laboratory, PTB, allowing US manufacturers the ability to get the chambers calibrated in the US and distribute them within Europe.

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X-Ray Standards

A new free-air ionization chamber has been designed to replace the Wyckoff-Attix chamber, which has been used at NIST as a primary x-ray standard for more than fifty years, to realize air kerma for x-ray beams of 50 kV to 300 kV. The dimensions and the parallel-plate design of the new chamber are identical to the Wyckoff-Attix chamber, but the materials are different. The chamber incorporates a unique guard bar and insulator design, and precision slides facilitate alignment and the direct measurement of the air-attenuation correction. The plans are complete for the new primary standard, and construction is contingent on the availability of funds. Once the new standard is constructed it will be fully evaluated in a parallel measurement arrangement until the correction factors are established and tested.

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Spectrometry of X-Ray Beams Used for Calibrations

Spectrometry measurements of the x-ray calibration ranges were initiated in 2006 using a high resolution HPGe detector both in the direct beam and at 90° using a Compton sppectrometer. Pulse height distributions were obtained for all the NIST and ISO beams produced by the NIST 100 keV and 300 keV x-ray generators, and have been unfolded and are in the process of being tabulated.

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Harmonization of Standards for the Air Kerma from ^{60}Co Gamma-Ray Beams

NIST participated in the EURAMAT key comparison of air-kerma and absorbed dose to water from ^{60}Co gamma-ray beams. Approximately 26 countries from around the world participated in this comparison, which started in January 2004 and was completed in the summer of 2008. Such international comparison allows one to assess differences in the realization of the primary standard quantities by the various National Metrology Institutes (NMIs) around the world. NIST served as the host laboratory for participants in the Sistema Interamericano de Metrología (SIM) regional metrological organization comprising national standards laboratories in the Americas, including Canada, Brazil, and Argentina. A set of instruments were shipped from the NIST to each of the facilities in a star-shaped pattern during the fall of 2007 and winter of 2008. The set included four chambers and two electrometers. Each chamber was calibrated with both electrometers and with the NIST system before and after the set was shipped to each of the SIM participants. The multiple measurements made at the NIST after the complete set was returned from each of the SIM participants reproduced very well, within 0.30 %. In early 2008 the instruments were returned to the EUROMAT coordinating laboratory, Országos Mèrèsügyi Hivatal (OMH), in Budapest, Hungary.

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New Safety System for Gamma-Ray Calibration Facility

The design of an improved safety system was started in the fall of 2007 for the NIST ^{60}Co vertical beam facilities. Integration of the new design into the existing system was required. The construction of the new safety system was completed and tested by the end of the spring of 2008. The new system automatically prevents access to the room in case of a source failure (e.g., the source fails to close). This major improvement adds additional safety to the existing system, which included multiple visible and audible warning indication of radiation exposure. In addition, new indicators have been added to warn those in the facilities that the rooms are being armed for radiation exposure. Heat, fire and smoke sensors have been installed and integrated in the circuit design so that the source will close automatically in the case of a fire, smoke or heat detection. The new system now includes a common key being used for accessing the room and controlling the source. This new feature ensures that the person arming the room is the only one that has control of the source. These improvements provide a safety system that exceeds the safety design of similar facilities found elsewhere.

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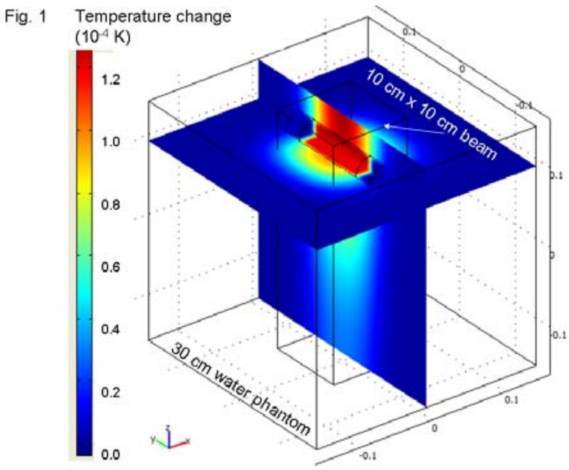
Advances in Water Calorimetry

A decade ago, Steve Domen developed a sealed-water calorimeter at NIST that was used to make the first determination of the absorbed dose at a point in water from ^{60}Co gamma-ray beams. This result has served as the NIST standard, and has been disseminated through the Accredited Dosimetry Calibration Laboratories (ADCLs) to the medical physics community. Since then, the adoption by the medical physics community of dosimetry protocols based on absorbed dose to water, rather than air kerma, has driven development of newer calorimeter designs incorporating modern technologies, such as lock-in detection and computer control. In an effort to leverage the capabilities of computer automation for repetitive measurements, we have been developing an approach to collecting and analyzing experimental data that emphasizes spectral characteristics of both signal and heat-transfer artifacts. Accordingly, physical processes such as conduction and convection are expressed as transfer functions that operate on the input radiation signal to produce a heating output signal that is attenuated and phase-shifted in the *frequency domain*. This approach is a parallel but more sensitive characterization of the distortion due to the artifacts in the conventional *time domain*.

The automated cyclic radiation delivery and frequency-domain technique have enabled a large number of measurements in a weak ^{60}Co source in a standard geometry of source-to-detector distance of 1 m and water surface-to-detector distance of 5 cm with improved statistical precision. Runs of 120 to 240 cycles of irradiations from shutter opening times of 60 s to 360 s have been analyzed both in time and frequency domains and are found to agree within the experiment uncertainties. Currently, the best statistical uncertainty achieved is 0.6 % per hour of data acquisition (60 s on/off operation). The 9000 runs in Room B034 yielded a standard deviation of the mean of 0.17 %, approaching Domen's 0.15 %. The uncorrected mean value of 0.577 Gy/min is 1.1 % below the transfer value from Domen's results, and we are assessing the corrections to be applied to this result, including thermistor calibration, attenuation, self-heating, heat defects, and heat conduction effects.



To evaluate the effect of heat transfer, a preliminary 3D finite-element modeling using a high effective conductivity to simulate forced convection of the outside water has been performed. With the vessel size used in the measurements, heat conduction can produce distortions of up to 2 % over the range of 30 s to 240 s shutter periods, depending on the value of the effective conductivity chosen. Fig. 1 shows two orthogonal slices across the cylindrical axis of the vessel depicting the spatial temperature distribution obtained from the simulation after subjecting the system to 30 s of radiation at 1 Gy/min dose rate and 30 s of cooling time thereafter. Studies continue on whether a steady state has been reached after a certain length of periodic exposures, to determine a steady system response.

Efforts have been underway toward separately quantifying the effects of heat conduction and convection and exploring experimental strategies and alternate, temperature-sensing technologies that would mitigate both of these phenomena. Both conduction and convection arise from thermal gradients within the calorimeter that are due to beam attenuation and build-up effects, steep dose gradients at the beam edges and sudden changes in heat capacity at the surfaces of non-water materials (such as thermistor probes and related hardware). The distortions they produce on measured temperature waveforms can lead to estimates of absorbed dose that lie above or below the true value. Estimating the effect of heat conduction on temperature waveforms is a straightforward problem analytically and numerically by comparison to convection, which involves mechanical motion of the water and nonlinear equations coupling the time-dependent temperature and water velocity. The extent to which convection affects the results has been the subject of some debate within the water-calorimetry community, with some numerical models suggesting that it arises even in calorimeters that are designed to work at 4 ^{o}C (where thermally induced changes in water density are very close to zero). Until quite recently, definitive experimental evidence distinguishing the roles of conduction and convection in water calorimetry was not available.

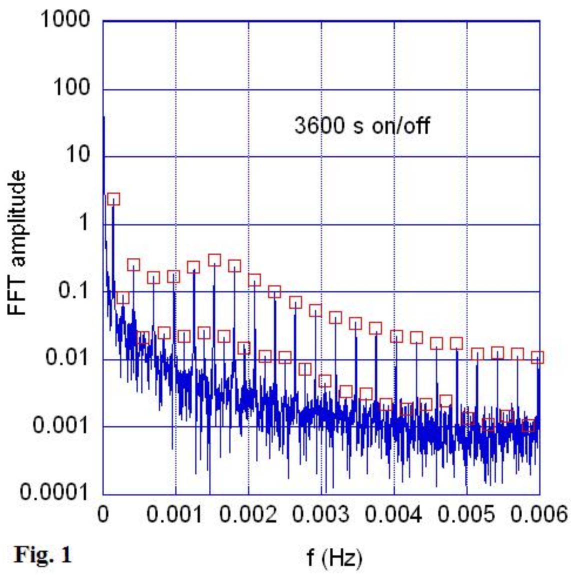
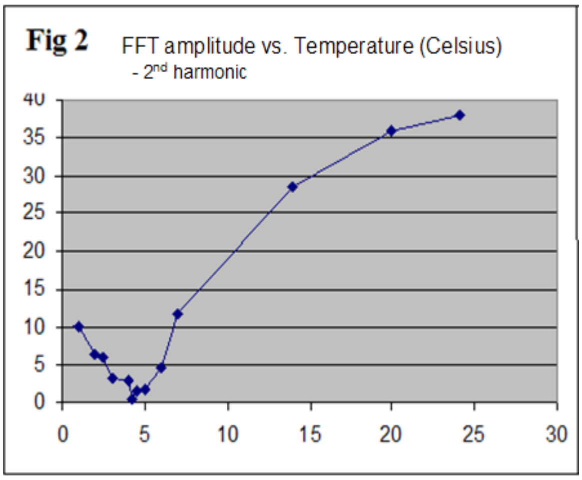


Fig. 1



By implementing periodic-chopper systems with both ^{60}Co and high-energy x-ray beams, we have been able to study the thermal-frequency response of the calorimeter and have discovered a unique spectral signature for convection. In the absence of heat-transport effects, the FFT of the time-domain temperature waveforms (or output spectrum) obtained from the calorimeter would be proportional to the FFT of the absorbed dose from the radiation source (or input spectrum) by a single, frequency-independent constant. Heat conduction, being a linear phenomenon, attenuates and shifts the phases of components of the input spectrum; however, the coupling of velocity and temperature fields that define convection leads to modulation products in the output spectrum at sum and difference frequencies. An example output spectrum is shown in Fig. 1, in which conditions that are conducive to the onset of convection – extended chopper period and operation of thermistor probes in an open phantom – result in tell-tale convection distortions of the spectrum: 1) a Lorentzian spectral envelope associated with oscillatory movement of water, and 2) the appearance of modulation products at even harmonics (between the larger peaks, which are at odd multiples of the chopper frequency).

In the usual metrological setting that defines standard practices for water calorimetry at most national metrology institutes, physical barriers are placed in the phantom around the thermistor probes, and the system is refrigerated to 4 ^{o}C in order to eliminate convection. Without experimental indicators of convection, however, the success of such measures can be judged only via numerical simulation. In a separate study, we have been using a precision temperature bath to study the thermal frequency-response of a water calorimeter with its convection barrier in place. Preliminary results, summarized in Figure 2, show the near extinction of convection-induced even harmonics in the vicinity of 4 ^{o}C. This study is expected to provide a means to investigate convection inside the water calorimeter and perhaps develop detailed corrections at room temperature that would allow us to operate a much simpler, room-temperature instrument.

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Direct Realization of Absorbed Dose in Water from High-Energy Photon Beams

Simultaneous charge and temperature measurements have been performed at the NIST Clinac with 6 MV and 18 MV photon beams at 5 cm and 10 cm below the water surface with an ionization chamber mounted at the same height as the calorimeter's thermistors, in order to ensure equal dose delivery. The ion-chamber values were obtained by transferring Domen's ^{60}Co standard through the standard TG-51 protocol to the high-energy photon beams. The calorimeter results were analyzed using the frequency-domain technique. Responses of both detectors track each other for one hour of 60 s on/off modulated radiation cycles for all conditions, with a systematically lower dose rate determined by the calorimeter. These results will be used in making corrections needed for heat transfer and other effects in the calorimeter. To continue the previous investigation of the dependence of the dose rate on irradiation time due to heat-transfer effects, a second set of measurements was carried out at various radiation durations with modulated cycles. The results are plotted on the left. Unlike the previous operation in the ^{60}Co beam, the outside water was not stirred here, resulting in a smaller spatial dose gradient and a relatively flat response to the period of radiation cycles. The simulated response using a 3D model with static water that does not include non-water materials is also

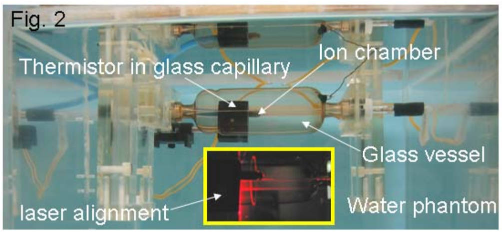
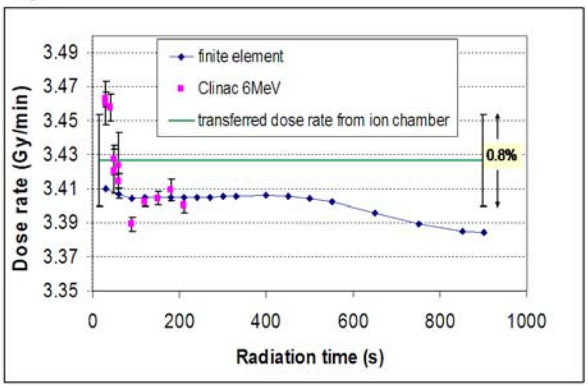


Fig. 3



shown in Fig. 3, normalized to the steady region of the calorimetry results. The simulated results indicate that the heat-transfer effect is not expected to cause deviations of more than 0.03 % when radiation times are below 400 s. The decreases at longer times are expected due to conduction cooling. However, the measured data show a 1 % increase at shorter times and a dip at 90 s; these variations might be accounted for with more complete 3D model simulations that include all the components.

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A New Dosimetry Technique – Ultrasonic Thermometer with μK Resolution in Water

The dosimetric standard at the radiotherapy level, absorbed dose to water in units of Gy (J/kg), is realized by measuring sub-mK temperature rise using a water calorimeter in a radiation beam. To date, the only mature technique that can attain the required μK resolution at room temperature, or a sensitivity of parts per 100 million, relies on temperature-sensing thermistors wired into a Wheatstone bridge and operated near an electrically balanced condition. Conventional water calorimeters based upon the original design of Steve Domen employ these thermistors sealed inside thin sheaths of glass, filled with high-purity water and placed inside a large water phantom under a radiation beam, forming the basis for measuring absorbed dose to water in all the metrology institutes around the world. With the thermistors and the associated housing and wiring being in the water where radiation heating takes place, heat-transfer effects must be corrected for. It is desirable to have an alternative non-invasive technique that can provide μK sensitivities and be free of the complications related to thermistor-based techniques. A NIST SBIR solicitation was put out and answered by Luna Innovations, which addresses this need by using a pulsed phase-locked loop (PPLL) controlled ultrasonic echo technique. This non-invasive approach reduces the complexity of the heat-exchange problem by eliminating non-water materials inside the water phantom.

The principle of operation of the ultrasonic thermometer is based on an empirical quadratic relationship between the speed of sound and the temperature in water at constant atmospheric pressure. The transmitted wavepacket reflects off the opposite wall in the phantom and is measured by the same transducer at the point of origin. Thus, changes in water temperature manifest as changes in the time of flight, which are registered by comparison to a reference waveform in the instrument. By adjusting the frequency of the reference waveform to achieve phase matching with the delayed wavepacket, the temperature-induced changes in the speed of sound can be measured by changes of frequency (for small changes, the two are proportional). Given that the frequency measurement can be resolved to 0.01 Hz or better, such as in a temperature-stabilized experiment, the temperature resolution therefore should be on the order of μK. A root-mean-square noise of 3.2 μK has been measured in a (30x30x30) cm^3 water tank by averaging over 400 s at a sampling rate of 4 per second. By comparison, the traditional set-up, involving two 10 kΩ thermistors (size usually less than 1 mm) in a Wheatstone bridge with a lock-in detection scheme, has a root-mean-squared noise in the output voltage of 50 nV with our measurement parameters, or about 3 μK. The transducer's power absorbed by water is estimated to be 4.5 μW, lower than the typical 25 μW produced by a thermistor. The width of the cross section of the sound wave is about 1 cm. Therefore, the ultrasound technique should be comparable to the thermistor technique in terms of the measurement resolution in temperature.

The Phase I award resulted in a prototype device that has demonstrated μK resolutions in a ^{60}Co beam at NIST. An ultrasound transducer can be attached to the wall of a standard acrylic water phantom of 30 cm in each dimension, with the electronic data-acquisition system storing temperature waveforms as the radiation is delivered cyclically, allowing time- and frequency-domain analysis as in the case of thermistor measurements. While thermistors measure the temperature rise at a point in space, the ultrasound technique measures the average temperature rise over the entire beam path. Simultaneous measurements with thermistors placed outside of the ultrasonic beam path were conducted, which show qualitative agreement between the two methods. Quantitative comparison can be made only if the spatial distribution of the radiation beam is known.

A factor that complicates the quantitative temperature determination is the radiation-induced convection in the water phantom. Unlike the common practice in water calorimetry in which a small glass vessel is used as a convection barrier surrounding the thermistors, the ultrasound path traverses the entire phantom and the water is allowed to convect when the temperature gradient reaches certain conditions, causing the body of water to move slightly in an oscillating fashion. Fig. 1 shows such an effect after a single shot of 60 s irradiation, after which the measured ultrasonic response continued to oscillate for almost an hour. The "natural" period of this oscillation is about 300 s, and it remains visible for almost an hour. The theoretical estimate of this phenomenon is under investigation, but is believed to give a value with the correct order of magnitude for this system.

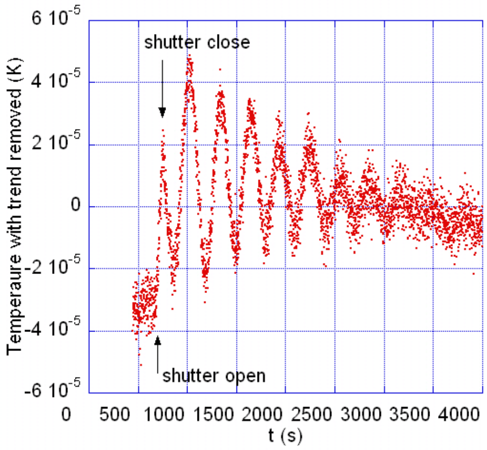

Fig.1 Observed convection in the large water phantom by ultrasound temperature measurements. The shutter opens for 60 s, the temperature rises initially, then enters into oscillations after the shutter closes.

A set of measurements was performed with the thermistor in the same depth as the ultrasound path, 10 cm below water surface, but laterally out of the path itself. To obtain the dependence of measured dose rate on shutter opening time, we varied the modulated shutter opening times from 60 s to 3600 s, again with the sound and thermistor data being recorded simultaneously. The dose rates obtained from frequency-domain analysis as a function of shutter opening time are plotted in Fig. 2. Similar to the past results obtained from using the standard practice of sealing thermistors inside a small vessel, the feature of a sudden drop-off after a maximum is observed here, but now is sharper, possibly due to the stronger convection cooling that directly affects the thermistor in open water than in a closed vessel. Frequency-domain analyses indicate an observable onset of convection starting at 240 s. Qualitatively, the thermistor and ultrasound data track each other, and at longer shutter opening times they reach the same asymptote, suggesting that some state of equilibrium is approached.

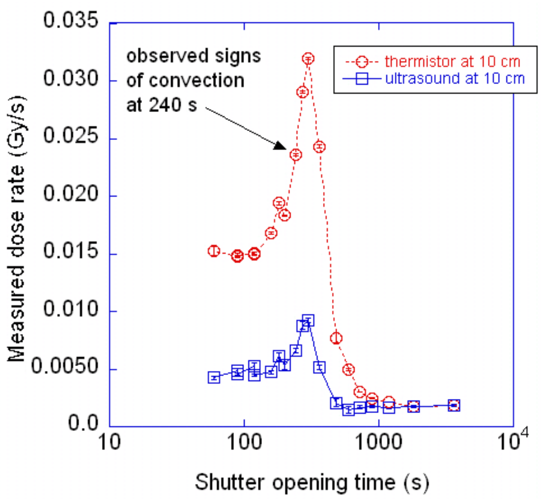

Fig. 2. Measured dose rate as a function of shutter opening times from ultrasound and the thermistor, both located 10 cm below water surface. The nominal dose rate is approximately 0.015 Gy/s at the measurement position.

Phase II of this project addresses the spatial information by employing an array of ultrasound transducers to permit tomographic reconstruction of the temperature profile in the water phantom. A prototype has been successfully tested at Luna in a laboratory setting using optical light as the heat source. With further development, the tomographic technique could be used for real-time radiation dose mapping in a clinical setting to provide crucial information for treatment planning that currently relies heavily on model calculations and point measurements with ionization chambers.

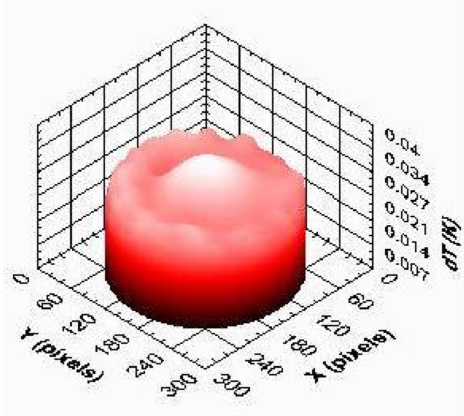

Fig. 5. Left: A 35.5 cm-diameter, 128-element submersible ultrasonic array for tomographic temperature reconstruction. Right: Temperature profile reconstructions in a water phantom from a fan beam tomographic acoustic experiment with 64 projections, 45 rays per projection with a 30 s exposure from a heat lamp as a radiation source. Area dimensions: 300 pixels =230(mm); Relative height of the temperature dome is about 8

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C. Homeland Security

X-Ray Security-Screening Standards for Homeland Security

With support from the Department of Homeland Security (DHS), the Radiation Interactions and Dosimetry Group has been developing technical-performance standards for four classes of x-ray security-screening systems: checkpoint cabinet, computed tomography, cargo & vehicle, and human subjects. Four ANSI working groups have been organized to develop national standards for technical performance, focusing particularly on image quality. The ANSI designations, domain of applicability, and specific image quality metrics that will be assessed are summarized in the table below.

Threat Domain	IEEE ANSI PIN #	Venues	IQI's (Image Quality Indicators) to be tested	IQ test methods & artifacts	Minimum performance requirements ?	Certification / Validation
Checkpoint	N42.44	aviation security, public buildings & events	resolution, penetration, organic-inorganic differentiation, wire- and hole-type IQI's	ASTM F792	YES	TSL
Computed Tomography (CT)	N42.45	screening systems using CT e.g, all checked luggage	radial, tangential, and slice resolution, noise, dual-E accuracy, streak artifact, CT # consistency, belt speed, attenuation	NEW	NO, security sensitive applications	TSL
Cargo/ Vehicle	N42.46	ports, borders, rail, trucks	penetration, spatial resolution, wire detection, contrast sensitivity, & resolution-contrast hybrid metric	NEW	NO, applications too diverse	NTS/DNDO
Human Subjects	N42.47	aviation, events, borders, prisons	TBD	NEW	YES	TSL

Table of ANSI standards under development and photo of the proposed test article for ANSI N42.45. This test article gauges image quality metrics such as CT number consistency, beam hardening, and CT reconstruction

Each standard will include both test methods and x-ray phantoms appropriate for the application; in some cases minimum performance levels are called out. This year the ANSI

N42.44 and ANSI N42.46 standards were completed and formally accepted through the IEEE balloting process. Shown in the accompanying figure is a prototype test article that is being designed and tested that is applicable to systems screening checked luggage (ANSI N42.45) using computed tomography (CT).

In related work, the group maintains a test bed for assessing the image quality of portable x-ray and imaging systems used by bomb squads for explosives and ordinance detection and for disarmament. The results of testing will be used to establish minimum image-quality standards and will be used to update a National Institute of Justice standard covering these systems. This facility has recently been augmented with an x-ray screening system of the type used in prisons and airports to scan humans without physically removing their clothing.

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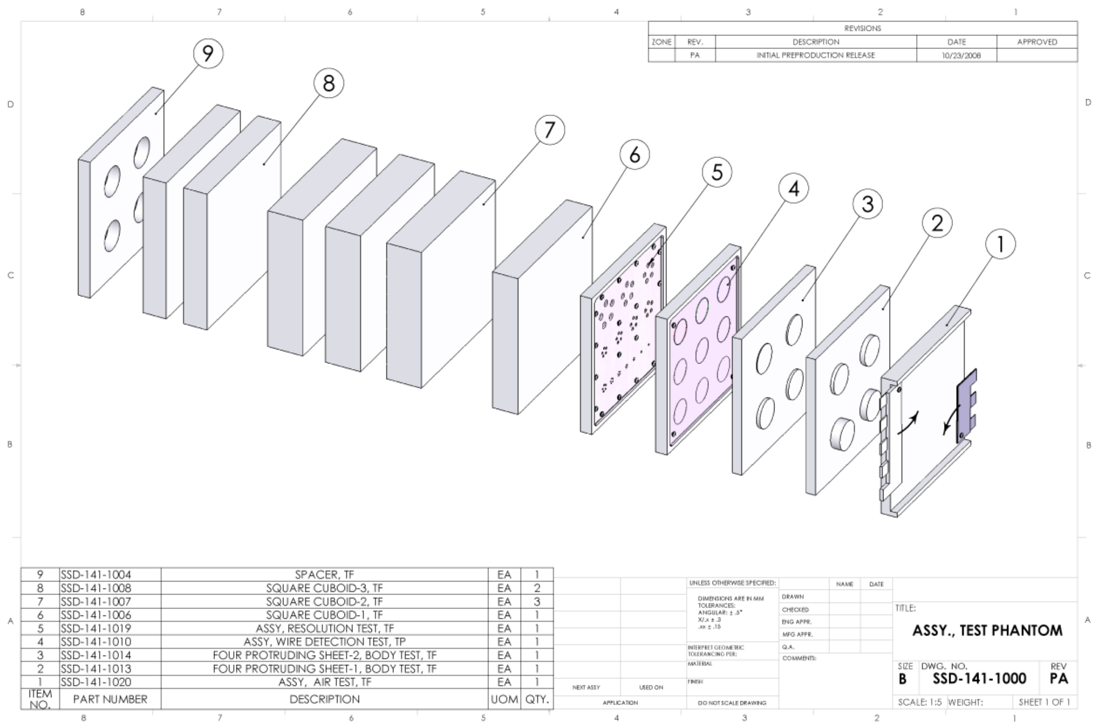
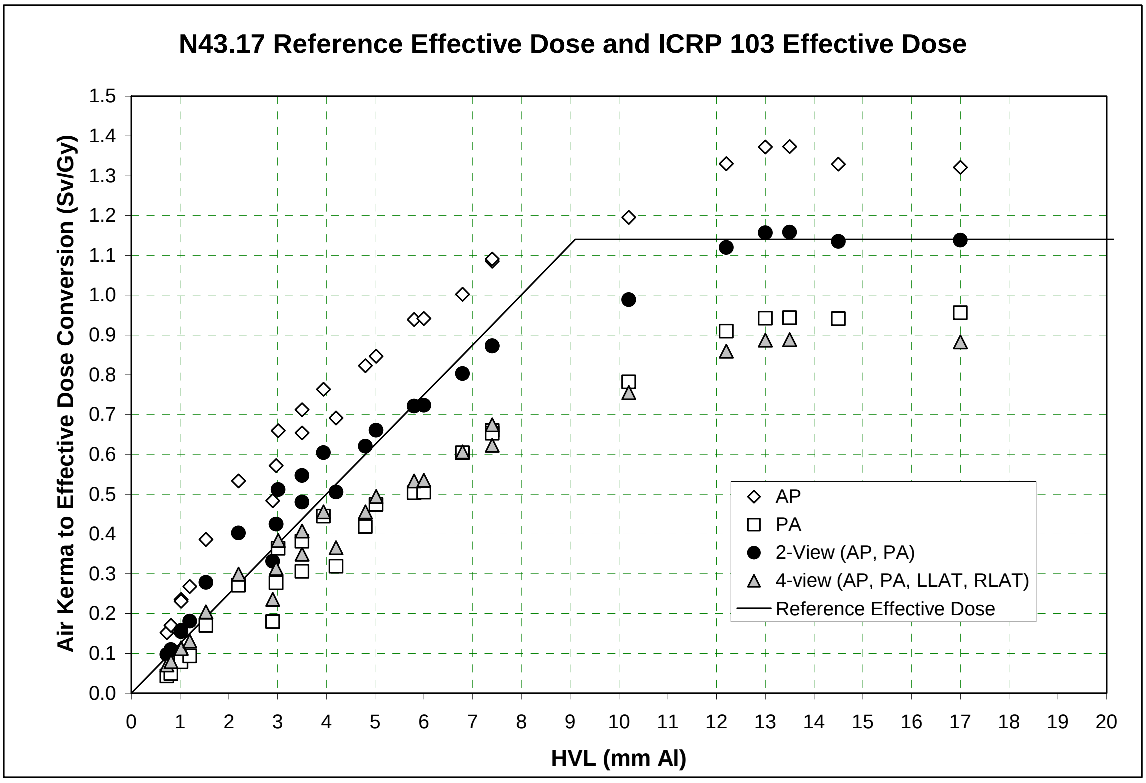
Radiation Safety and Measurements for Security-Screening Applications

The Radiation Interactions and Dosimetry Group participated in the development of various standards for security-screening systems employing x-ray and gamma radiation. In October 2008 NIST submitted two draft standards to the respective ANSI Committees for balloting: ANSI/HPS revision of standard N43.17, "Radiation Safety for Personnel Security Screening Systems Using X-Rays" and ANSI/IEEE standard N42.47, "Standard for Measuring the Imaging Performance of X-Ray and Gamma-Ray Systems for Security Screening of Humans." Whereas the N43.17 revision was necessary because of advances in technology leading to many new system configurations, N42.47 was submitted as a new standard.

The N43.17 effort resulted in a novel method for approximating effective dose from whole-body x-ray irradiation, based on measurements of the half-value layer and air kerma. The N42.47 effort resulted in a novel test object, the pentalith, for measuring the spatial resolution of images. The Radiation Interactions and Dosimetry Group organized and participated in numerous meetings leading to these two draft standards as well as meetings of the ANSI/HPS N43.16 Working Group working on a radiation-safety standard for non-intrusive cargo inspections. Also, NIST staff conducted third-party radiation-safety evaluations of a two second-generation, body scanners under an Interagency Agreement with the Transportation Security Administration.



The imaging test object developed for ANSI/IEEE standard N42.47



The ANSI N43.17 "Reference Effective Dose" compared to data calculated for many standard x-ray spectra.

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Advanced X-Ray Systems for the Detection of Special Nuclear Materials

The Radiation Interactions and Dosimetry Group provides support to the Domestic Nuclear Detection Office of the Department of Homeland Security for their Cargo Advanced Automated Radiography System. This system employs only passive x-ray inspection to detect the threat of nuclear material. Our support consists of Monte Carlo calculations and of measurements. The initial calculations and measurements are part of an effort to determine the radiation safety of such systems.

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Air-Kerma Rate from Small Radioactive Sources Used for Homeland-Security Applications

Recently published air-kerma measurements made at NIST help ensure the correct testing and calibration of portal radiation monitors. Portal radiation monitors are currently used at entry ports and land borders to prevent illegal transport of radioactive materials into the country. To ensure measurement accuracy, they must be calibrated in terms of the quantity air kerma. The calibration relies on the use of small radioactive sources for which the air kerma rate at a given distance must be well known. These sources are placed at a well-defined distance from the portal monitor so that the reference air-kerma rate value and the rate measured by the portal monitor can be compared. Manufacturers of the radioactive sources do not provide the air-kerma rate. Instead they provide the activity of the source, traceable to NIST, which is expressed in units of bequerel (or the older unit of curie). It is the user's responsibility to determine correctly the air-kerma rate from the source from the value of activity provided by the source manufacturer. Conventionally, an air-kerma rate is derived from the use of tabulated (calculated) values of the so called air-kerma-rate constant (a.k.a. gamma-ray constant), which applies to an idealized point source in a vacuum. Our studies find large variations in the published values of calculated air-kerma rate constants, and that portal monitors can be calibrated incorrectly if care is not taken in how such values are used. Air-kerma-rate measurements from our studies can be used to validate published calculated values.

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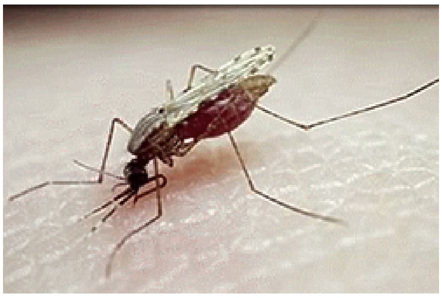
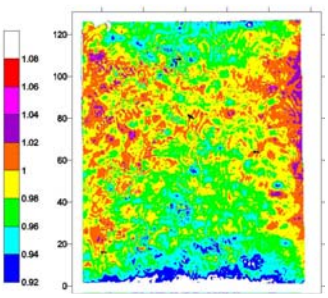
D. Radiation Dosimetry for Industry and Protection

Absorbed-Dose Measurements to Support Biologics Research

The Radiation Interactions and Dosimetry Group has been working with Maryland-based biotech firm Sanaria Inc., which is creating a new type of vaccine that shows promise of being more effective than current malaria vaccines. The new vaccine involves irradiating mosquitoes containing the parasite Plasmodium falciparum, the most dangerous species of parasite that causes malaria. Specifically, the group performed measurements to assist Sanaria in assuring a minimum delivered dose of 150 Gy to all mosquitoes in the Sanaria ^{60}Co irradiator.





First, dose-mapping measurements were performed with GafChromic films in vertical sheets. The films were analyzed using the LKB laser scanning densitometer, and results gave details on relative dose uniformity for the entire volume of the irradiation vessel. The film results gave relative positions for minimum and maximum dose inside the chamber. With this data, the Group was able to recommend a shift in the vessel position to allow for a more uniform dose. The result was a shorter irradiation cycle to save time, plus less overdosing that improves process quality.

Next, a series of experiments were done to determine the ratio between doses for dosimeters placed in the minimum-dose position inside the vessel versus dosimeters placed on the outside surface of the vessel. The successful determination of this ratio and its statistical uncertainty allows for future irradiations to be done with just the outside dosimeter as a monitor. This is critical to the manufacturing process, as there would be no option to have dosimeters inside the vessel in the presence of the infected mosquitoes.

Since that initial work in 2006, the group has provided Sanaria with NIST alanine transfer-dosimeter measurements on more than two dozen occasions. These measurements have served to support Sanaria's quality-assurance tests that ensure the desired dose is being delivered to the mosquitoes. In Spring 2009, the project begins the second round of human clinical trials.

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Applications of NIST Alanine/EPR Dosimetry to the Irradiation of Blood and Blood Products

At present, gamma irradiation of blood products is the only procedure known to prevent transfusion associated graft versus host disease (TA-GVHD). The most common irradiation sources are Co-60 and Cs-137. Most blood centers rely on a nominal dose of 25 Gy with no less than 15 Gy delivered to any area of the bag for these radiation beams to inactivate lymphocytes in cellular products for transfusion.[1] International Specialty Products (ISP) is a commercial manufacturer of a variety of film products that are used for the verification of irradiation of blood or validation of a blood irradiator's performance.

In 2004, NIST was contacted by ISP with the possibility of using alanine dosimetry to provide traceability of the ISP dose-mapping service for blood irradiators to national standards. NIST continues to provide measurement services of alanine dosimeters that have been co-located with ISP films in blood-irradiator canisters.

[1] Guidelines on gamma irradiation of blood components for the prevention of transfusion-associated graft-versus-host disease. BCSH Blood Transfusion Task Force. Transfus Med 1996;6:261-71.

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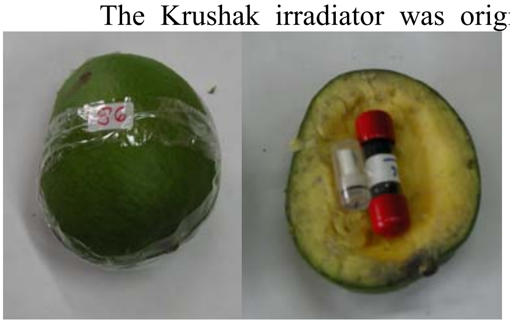
Food Dosimetry Project in Support of USDA Effort to Allow Import of Irradiated Mangoes

In March of 2007, the Radiation Interactions and Dosimetry Group agreed to assist the USDA and sent staff to India to perform on-site dosimetry to certify the treatment process of irradiating mangoes in India to allow for export to the U.S. markets. To protect the U.S. agricultural industry, these mangoes must be treated with ionizing radiation to control pests that include a weevil commonly found in the fruit's pit. Gamma-irradiation treatment facilities in India had to demonstrate that their facility, treatment plan, and quality-control system could ensure that the fruit would receive an absorbed dose of radiation that was high enough to kill or sterilize the pests while keeping the fruit palatable. India is the world's largest producer of mango, and the Alphonso variety being treated for export is the considered the king of mangoes for its outstanding flavor and texture. NIST's role was to measure the dose distribution from the Indian irradiator and the absorbed dose inside the mango pit itself.

The Krushak irradiator was originally commissioned for lower dose operations such onion- and potato-sprout control and had been recently resourced to go from about 50 kCi to 266 kCi of ^{60}Co. The irradiator carries products along a conveyor system of totes, with each tote holding about 30 boxes of mangoes in 3 columns and 10 rows.

The work involved two dosimetry systems: optichromic dosimeters for field measurements and alanine pellets for reference-class transfer



measurements. The two NIST dosimeters were co-located with the Indian ceric-cerous dosimeters at specific box locations beside the fruit and directly inside the fruit. Several times over the two-week effort in India, the alanine dosimeters were express-shipped to NIST for absorbed-dose certification. These data enabled the USDA/NIST team to make field adjustments of the process and to set process-control factors that would guarantee proper treatment of future mango loads.

The first Indian mango shipment arrived four months earlier than the target date set in the March 2006 agreement between USDA and the Indian Ministry of Agriculture. This event marked a milestone for irradiation technology used in safeguarding U.S. agriculture. These mangoes are the first fruits to be irradiated for importation into the United States.

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The Temperature Coefficient for Alanine Film and Pellet Dosimeters at Elevated Temperatures

Correcting the response of a dosimeter for the average temperature during irradiation processing improves the accuracy of the dose measurement. The relationship between the dosimeter's radiation response to the absorbed dose and its temperature during irradiation is termed the irradiation temperature coefficient. This temperature coefficient is typically expressed in percent change per degree. The temperature rise in dosimeters irradiated with high-intensity ionizing radiation sources can be appreciable. This is especially true for electron-beam processing in which dosimeter temperatures can approach 80 °C. However, the temperature coefficients determined for commercial dosimeters have been characterized only up to ≈50 °C. A comprehensive study of film and pellet dosimeter temperature coefficients has been completed. The data revealed modest (0.5 % – 1.0 %) deviations from the predicted value at temperatures above 70 °C for absorbed doses of 1 kGy and 20 kGy. These data further establishes alanine dosimetry as the system of choice for extreme industrial irradiation conditions.

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Temperature Corrections and Estimating Uncertainties for Industrial Radiation-Processing Dosimetry

Because dosimeter response is affected by the average temperature of the dosimeter during irradiation, the accuracy of this adjustment impacts the quality of the dose measurement. The relationship between the dosimeter's radiation response to the absorbed dose and its temperature during irradiation is termed the irradiation temperature coefficient. This temperature coefficient is typically expressed in percent change per degree. The temperature rise in dosimeters irradiated with high-intensity ionizing radiation sources can be appreciable; however, the temperature during irradiation is often difficult or impractical to be measured directly. In the absence of a direct measurement, an estimation of the irradiation temperature is often employed to make this correction for the computation of absorbed dose. Since this aspect of routine dosimetry is difficult to assess in an industrial setting, a study simulating those conditions was undertaken to determine the quality of these data manipulations and to estimate the associated uncertainties. Industrial temperature profiles were obtained from industry contacts and simulated in NIST Gammacells. Typical temperature correction methods used by industry operators were employed and compared to the actual temperature corrections made under controlled conditions at NIST. As anticipated, the maximum irradiation temperature is the least accurate selection for use in dosimetry calculations. The irradiation temperature determined by the mean of the initial and maximum temperatures was equivalent to other formulas commonly used in industry with regard to determining an irradiation temperature that would lead to the most accurate estimate of absorbed dose. In general the differences were comparable to the measurement uncertainty, and the main value this work is that these data provide a basis for an informed assessment of this Type B uncertainty common to industrial dosimetry

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Testing a Method for Establishing e-Traceability to NIST High-Dose Measurement Standards

To meet the rapid turn-around time needs, yet maintain high accuracy and minimal uncertainties, an internet-based system for remote dose certification of industrial radiation sources using a table-top EPR/alanine analyzer is being developed at NIST. In order to establish traceability to NIST high-dose measurement standards, each Bruker e-Scan instrument used in industry will be calibrated to the NIST reference-dosimetry system/instrument. A comprehensive method for customer-to-NIST calibration-curve conversion has been established by determining the optimal computational method for determining a dosimeter measurement conversion factor (MCF) between the reference and remote instrument calibrations. The uncertainty attributed to applying the MCF in the response conversion has been evaluated and used to establish an overall uncertainty budget for such an internet-based service.

Testing the creation of a NIST standard reference curve has been conducted by creating multiple insert calibration sets and varying the number of dosimeters measured at each dose point before applying the mathematical fit to create the calibration curve. The conclusion from this testing was that eight dosimeters at each dose point of the calibration curve was optimal for increasing the accuracy, as well as decreasing the uncertainty, associated with creating the standard calibration curve. Utilizing the two separate e-Scan systems at NIST, testing the calculation and application of the MCF has been conducted by creating a customer insert set, similar to that which would be sent during an actual calibration event, and exporting the results in order to perform the MCF calculation. This testing has yielded results that show good stability of the MCF calculation for the PL, and PH inserts and promising MCF application results for the PV and FH inserts. These dose ranges (PL, PH, PV, and FH) are widely used in the radiation processing industry for pellet and film dosimeters and have been tested first; however, they are only 4 of 9 commercially available dose ranges, so additional testing is still on-going.

Testing the electronic certification process is conducted by measuring a series of unknown test dosimeters, applying the MCF, and calculating dose from the NIST standard reference curve. These tests will also be performed for all of the commercially available inserts, and will serve as guidelines for the operational aspects of this future service. Completion of the client-server software system occurred in 2007, and will undergo beta-testing in the near future. NIST is working with the spectrometer manufacturer for future inclusion of the client-server software system into the spectrometer operational software, so that NIST can perform a complete beta-test and evaluation of the Internet-based high-dose transfer dosimetry service. Also, future work includes the design, development and inclusion of NIST analysis software in order to streamline the dose certification process for this internet-based service.

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An Irradiation-Temperature Study of the Thin-Film B3 Radiochromic Dosimeter

The B3 radiochromic dosimeter is used by many industrial irradiation facilities as a routine dosimeter for high-energy radiation (gamma rays, electrons and x-rays) processing. The B3 dosimetry system is easy to use and inexpensive to operate. However, the dosimeters are sensitive to several environmental influences including, relative humidity, ambient light, and irradiation temperature, and they must be thermally annealed postirradiation at a specific temperature. The calibration of these dosimeters is often done *in situ* with alanine transfer dosimeters supplied by a national standards laboratory. As such it was considered important to examine the B3 system in greater detail in the NIST irradiation facility where there is more precise control over environmental and irradiation conditions. Since the literature data are limited, a better understanding of the relative effects of irradiation temperature for these dosimetry systems would be valuable in resolving measurement differences. For this study NIST collaborated with GEX Corporation, the manufacturer of B3 radiochromic dosimeters. Dosimeters accompanying products that undergo the industrial irradiation process can experience temperature rises up to 60 °C. Using the NIST high-dose-rate ^{60}Co Gammacell source and its advanced temperature control system, the temperature dependence for B3 dosimeters irradiated from ambient temperatures up to 70 °C in the absorbed-dose range of 10 kGy to 70 kGy was measured. A complex relation between dosimeter response, absorbed dose and irradiation temperature was observed. In some temperature-dose regions the temperature coefficient (response change per unit temperature) was positive, while in other regions (primarily high dose and high temperature) the temperature coefficient was negative. GEX Corporation and NIST are currently reviewing the data and its implications for dosimetry and calibrations.

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Dose/Dose-Rate Effects in Alanine Dosimetry

NIST developed the alanine dosimetry system in the early 1990s to replace radiochromic-dye film dosimeters as its primary transfer absorbed-dose certification system. Later in the decade the alanine system was firmly established as a transfer service for high-dose radiation dosimetry and an integral part of the internal calibration scheme supporting these services. Over the course of the last decade, routine monitoring of the system revealed a small but significant observation that, after examination, led to the characterization of a previously unknown absorbed-dose-dependent, dose-rate effect for the alanine system. This work characterizes a complex relation between the radiation chemistry of crystalline alanine and the applied dose rate as a function of absorbed dose. This effect appears intrinsic to alanine itself and is not dependent on the form or formulation of the alanine dosimeter. These studies suggest that the production of one or more of the alanine radicals is dependent on the dose rate and that this rate effect becomes significant above 5 kGy.

Typically high-dose-rate calibration sources maintained by National Measurement Institutes (NMIs) are calibrated against low-dose-rate sources that are used to realize the gray with a primary standard (e.g., calorimeter). If a dose rate is established for a high-rate gamma calibration source by comparison to dosimeters calibrated in a low-rate source at absorbed doses in the kGy range, errors could be introduced in the dose rate for the high-rate calibration source. If this calibration source is in turn used for calibration-service work, a dose-dependent error would be further transferred to industrial customers. For the NMI that has ensured that their dose rates are not influenced by this dose-rate effect, two considerations remain. First, caution would be advised to avoid using alanine dosimeters at high doses (>5 kGy) for transfer calibrations of low-dose-rate (< 2 Gy s^{-1}) sources, and, second, one should avoid using a gamma source with a low-dose-rate to calibrate alanine dosimeters. The most significant impact of this finding lies in international comparisons. Considering that the previous international high-dose dosimetry comparison in 1997 did not take this effect into account, it is recommended that for follow-up NMI comparisons the calibration schemes of the participants should be first be examined. NIST is leading a NMI comparison in 2008 to examine the possible influence of dose rate in advance of a larger comparison planned in 2009.

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Advancements in Alanine-Film Dosimetry

The film-based form of the alanine dosimeter has attributes that are attractive to most industrial users. The ease of handling, resistance to mechanical failure, and individual barcode labelling are all desirable features for the harsh industrial environment. The weakest attribute of this system is the reduction in sensitivity that is inherent to the reduced mass of alanine material in a film and a reduction in precision relative to the alanine-pellet system. Our initial investigations sought to learn if possible inconsistencies in the manufacturing process are responsible for the loss in precision. If the mass of alanine dispersed in the film had a spatial variation along the length of the film then the strong sample-position sensitivity of an EPR microwave-resonator sample chamber could contribute to an observed loss in precision. Building on this assumption, alanine film dosimeters were irradiated to a low dose (1 kGy), and the resulting signal was used as a measure of the individual film's sensitivity. A normalization factor was computed for each dosimeter that could be applied to subsequent measurements of the films after additional doses were applied. While the results did show some promise (the precision was significantly improved), the results were inconsistent over the dose range studied. Because these results may be reflective of the dose range limitations of the e-Scan EPR spectrometer used for the measurements, the work will be repeated on a more advanced spectrometer. A new EPR spectrometer has been acquired by the Ionizing Radiation Division, and this spectrometer will be dedicated to alanine-film research. It is becoming increasingly likely that alanine film will play an important role in the dosimetry calibrations of industrial low-energy electron-beam accelerators, and this research will provide key information toward this application and others.

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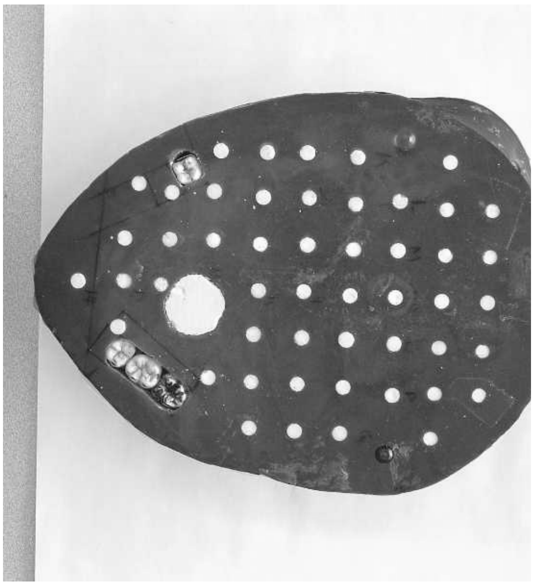
Absorbed-Dose Profiles in Teeth for Emergency Biodosimetry

The energy of the incident gamma radiation is considered to be a factor that influences the accuracy of the Electron Paramagnetic Resonance (EPR) dose-reconstruction technique with teeth. Frequently the spectrum of the gamma field is unknown and assumptions are needed to convert the EPR-reconstructed tooth-enamel doses into reference values and/or doses for other organs and tissues. As is well known, the attenuation of the photons passing through teeth varies with the photon energy, from several percent for energies of hundreds of keV to several tens percent or more for energies of a few tens of keV, resulting in different dose profiles in the teeth. Presumably, such differences can provide information on the radiation energy associated with the accidental exposure, which could be assessed directly from EPR measurements of dose profiles in teeth. Dose profiles in teeth have been experimentally and theoretically studied for different energies and geometries of incident x- and gamma-rays. These experiments were conducted with teeth inside of an Alderson phantom (see Figure) using monodirectional radiation beams at selected energies; they revealed two effects: an apparent lack of dose attenuation between the buccal and the lingual sides of the teeth for energies higher than 120 keV, and an attenuation between first and last tooth layers for low-energy beams in the range from 0.28 to 0.57 keV. Monte Carlo simulations confirmed the experimental data and provided dose profiles for other energies and geometries. In particular, exposure in a rotational radiation field produces pronounced dose profiles only for energies lower than 60 keV. These data may prove useful for a tooth exposed to radiation with an unknown spectrum, as it may be possible to use the corresponding dose profile to infer the average energy of spectrum. The data indicate that if dose profile is flat, it is possible only to conclude that the average energy is greater than 120 keV. If the profile is pronounced, it is possible to conclude that the average energy is lower than 120 keV, but its value will depend on the geometry of irradiation. In addition, if there are several sources that contribute to the absorbed dose profile, for example a high-energy gamma source superimposed with a low-energy x-ray source, the result will be less conclusive. This study was a collaborative effort between NIST, the National Cancer Institute and the Scientific Center of Radiation Medicine, Kiev, Ukraine.



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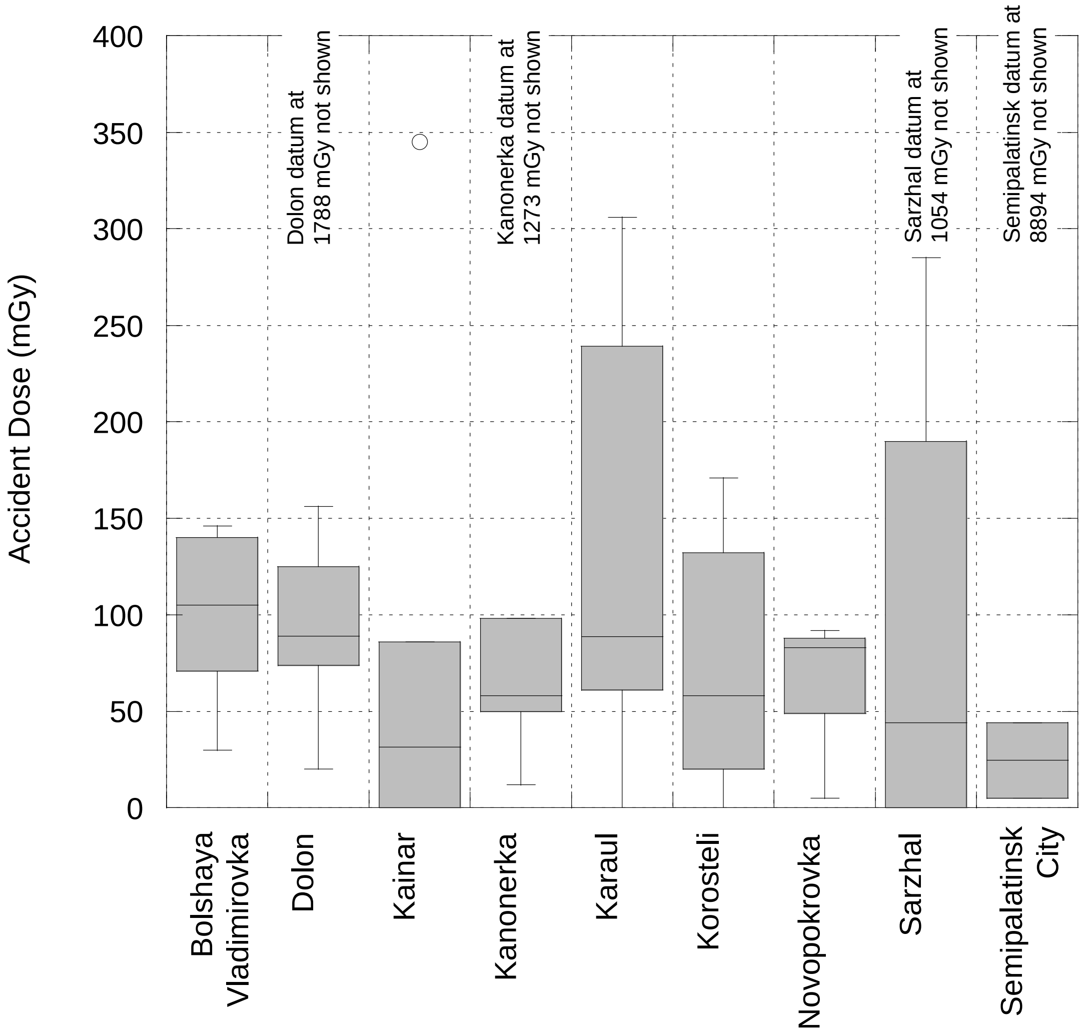
Biodosimetry of Semipalatinsk Nuclear Test Site Inhabitants

The external dose to the teeth of inhabitants of settlements near the Semipalatinsk Nuclear Test Site (SNTS) was assessed using the electron-paramagnetic-resonance (EPR) dosimetry technique to assess exposures associated with radioactive fallout from the test site. For this study, tooth doses have been reconstructed for 103 persons, with all studied teeth having been formed before the first nuclear test in 1949. Doses above that from natural background, termed "accident doses," were found to lie in the range from zero to approximately 2 Gy, with one exception: a dose for one person from Semipalatinsk City of approximately 9 Gy. The variability of reconstructed doses within each of the settlements demonstrated heterogeneity of the deposition as well as variations in lifestyle. The village-mean doses for the settlements were in the range from a few tens of mGy to approximately 100 mGy. This study was a collaborative effort between NIST, the National Cancer Institute and the Scientific Center of Radiation Medicine, Kiev, Ukraine.



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The Influence of Sunlight on the Biodosimetry of Teeth

The common consensus among experts is that front teeth should not be used for retrospective EPR dosimetry due to possible unknown EPR-signal contributions from ultraviolet (UV) components of solar radiation. Previously published work reported that solar exposure can produce paramagnetic centers that are spectroscopically identical to those generated by gamma-ray radiation. This effect sometimes renders front tooth samples as unusable or their data as questionable/unreliable. A method to discriminate the solar contribution to the dosimetric signal would expand the use of EPR dosimetry to front teeth and improve the confidence of the data. In this study it was shown that UV light not only produces a signal that contributes to the dosimetric EPR signal in tooth enamel but also produces distinctly separate EPR signals. It was found that both the dosimetric and UV-specific signals increased linearly with UV dose in the dose range studied. Because the UV-specific signals are spectroscopically distinct from the dosimetric signal, they may be used to quantify the UV dose in front teeth. In addition, the attenuation coefficient was measured for tooth enamel over the UV range of wavelengths. This information can be used to mechanically or chemically remove the surface layer of the enamel to significantly reduce the UV-dose contribution to the enamel sample to be measured. A test of the spectroscopic method to separate UV and gamma doses can be done using the low-intensity UV-specific signals. This separation was successfully performed on two of eight front teeth from Semipalatinsk-area inhabitants that resided in high-dose locations. The remaining six samples were found to have accumulated doses below 200 mGy; this is the current sensitivity limit for this technique. This study was a collaborative effort between the NIST Physics Laboratory, NIST Building and Fire Research Laboratory, the National Cancer Institute, and the Scientific Center of Radiation Medicine, Kiev, Ukraine.

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Proficiency Testing of Calibrations in ^{137}Cs Gamma-Ray Beams

In early 2006 NIST completed the design and construction of a new calibration range used for air-kerma rates approaching environmental levels down to 0.2 uGy/h. This facility allows expanding the range of air-kerma rates available at NIST for Cs-137 beams used for the testing and calibration of radiation-detection instruments in radiation protection and homeland-security applications. Prior to the construction of this facility, secondary standard calibration facilities (SSCFs) in the U.S. interested in calibrating large-size chambers would send their instruments to other primary laboratories around the world. In particular K&S, one of the SSCFs accredited by the Health Physics Society, calibrated their chambers at the National Physics Laboratory in the United Kingdom. During the spring of 2008 NIST, using its newly developed facility, conducted the first proficiency test for K&S. The proficiency test assesses the capability to transfer the measurement from a primary measurement. The proficiency-test protocol involves sending an ionization chamber from NIST to the laboratory under test, for which the response of the instrument is unknown. The testing laboratory calibrates the chamber at their facility and then returns it to NIST. Once the test is completed, the level of agreement between NIST and the testing laboratory is reported. The relative agreement found during this first test between K&S and NIST was of 0.2 %. In addition to this proficiency test, NIST continued to perform proficiency tests for other calibration facilities during 2008 including: Fluke Biomedical (a manufacturer of radiation detection instruments), the Ohio Emergency Management Agency, and two of the SSCFs accredited by the Conference of Radiation Control Program Directors.

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Support of the Navy Calibration Program

The headquarters operation of the U.S. Navy calibration program was recently moved to the Naval Weapons Facility in Yorktown Virginia. To ensure that they continue to be able to transfer air-kerma measurements from NIST, they consulted NIST staff on the setup and operation of their new facilities. This included a visit from the Navy staff to NIST in the summer of 2007 and a subsequent visit of NIST staff to the Naval Weapons Facility in the summer of 2008. This latter visit involved a technical review of the Navy air-kerma-calibration program. In addition, an informal blind test was performed by NIST staff at the Yorktown facility during the visit. The Navy’s calibration program relies on the calibration of ionization chambers that are later used by the Naval Weapons Facility for characterizing cesium irradiators at other Navy sites, which are subsequently used for calibrating instruments throughout the Navy. Both the technical review and the measurements performed during the visit provide confidence in the newly established calibration program and ensure ultimately traceability of their measurements to national standards.

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^{137}Cs Gamma-Ray TLD Irradiations for the Navy Dosimetry Program

For the past several years NIST has provided radiation measurements in support of the Navy quality-assurance program for testing thermoluminescent dosimeter (TLD) systems. The TLD model DT-526 is a calcium fluoride solid-state dosimeter that has been used by the Navy since 1973 for monitoring the exposure of personnel working at naval shipyards under the US Naval Nuclear Propulsion Program (NNPP) and at other NNPP sites. In support of this program NIST provides monthly irradiations of TLDs that are later used to test TLD readers located at the various sites associated with the NNPP. The test is coordinated between NIST and Navy personnel at the Naval Surface Warfare Center in Bethesda.

The monitoring of radiation exposure for Navy personnel not associated with the NNPP is provided by the Naval Dosimetry Center (NDC) in Bethesda Maryland. NIST assists the NDC with measurements to support the implementation of a quality-assurance program based on a new TLD system that uses the model DT-702 TLD for personnel monitoring. The model DT-702 technology has improved significantly relative to the older DT-526 technology. The newer dosimeters provide more accurate readings, better stability, energy discrimination and a lower detection limit.

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Calibration of Beta-Particle Sources and Instruments for Radiation Protection

A calibration service for protection-level beta-particle sources and instrumentation has been in place for several years. The measurement system is automated, and capable of measuring extremely low absorbed-dose rates. The automation control software has been rewritten in LabView code. The second-generation beta-particle secondary-standard system (BSS2), which includes the isotope ^{85}Kr, is now utilized routinely for calibrations and research into standard extrapolation-chamber data-handling techniques. The sources were calibrated both at the Physikalisch Technische Bundesanstalt (PTB) and at NIST, allowing a direct intercomparison of calibrations. The systems are also being used for the dosimetry characterization of a photo-stimulatable luminescence phosphor imaging system. The standardized techniques developed at PTB and NIST are now included in an International Organization for Standardization draft standard and are being implemented in the NIST calibration service. The calibration service has been thoroughly re-documented for inclusion in the Division Quality Manual. NIST participated successfully in a EUROMET supplementary comparison of absorbed-dose rate in tissue for beta radiation.

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Tosh, R.E., and Chen-Mayer, H.H., "What spectral methods can tell us about heat transfer effects in water calorimeters," Proc.of Absorbed Dose and Air Kerma Primary Standards Workshop, Paris, 9-11 May (2007).

Tosh, R.E., and Chen-Mayer, H.H., "Frequency-domain characterization of heat conduction in sealed water calorimeters," Nucl. Instr. Meth. A, **580,** 594-597 (2007).

Tosh, R.E., and Chen-Mayer, H.H., "Heat transfer effects in a water calorimeter for measuring the absorbed dose of therapy-level radiation beams," Proc. Comsol Conference, Boston, MA, 4-6 October (2007).

Tosh, R.E., and Chen-Mayer, H.H., "A transfer-function approach to characterizing heat transport in water calorimeters used in radiation dosimetry," in *Thermal Conductivity* **29** / *Thermal Expansion* **17**, Eds. Koenig, J.R., and Ban, H., DEStech Publications, pp. 499-509 (2008).

4. Invited Talks

Bateman, F., "NIST accelerator diagnostics and quality assurance testing," 16th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards, Gaithersburg, MD, October 2007.

Cerra, F. "The Health Physics Society position on the use of ionizing radiation for screening people for security purposes," Nuclear and Radiation Studies Board of the National Academy of Science, Washington, DC, 4 April 2007.

Cerra, F. "Health physics of imaging systems for personnel security screening," Mid-Year Meeting of the Health Physics Society, Oakland, CA, 27 January 2008.

Chen-Mayer, "Uncertainties in water calorimetry," 15th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards, Gaithersburg, MD, October 2006.

Chen-Mayer, "Studies of heat transport from a point source in the NIST Domen water calorimeter," Absorbed Dose and Air Kerma Primary Standards Workshop, Paris, May 2007.

Chen-Mayer, “A high-resolution ultrasonic thermometer for measuring absorbed dose in water calorimeters,” Absorbed Dose and Air Kerma Primary Standards Workshop, Paris, May 2007.

Chen-Mayer, “Experimental observations of convection in an ultrasound thermometer for measuring absorbed dose to water,” 49th Annual Meeting of the American Association of Physicists in Medicine, Minneapolis, MN, July 2007.

Chen-Mayer, “NIST water calorimeter update: measured dose rate as a function of exposure time,” 50th Annual Meeting of the American Association of Physicists in Medicine, Houston, TX, July 2008.

Desrosiers, M. “An absorbed-dose / dose-rate dependence for the Alanine-EPR dosimetry systems,” International Meeting on Radiation Processing, London, UK, September 2008.

Desrosiers, M. “Discovery of an absorbed-dose / dose-rate effect for alanine dosimetry,” American Society for Testing and Materials, Tampa, FL, January 2008.

Desrosiers, M. “Radiation accidents: how bones and teeth are used to measure human exposures,” Morehouse College, Atlanta, GA, November 2007.

Desrosiers, M. “Discovery of an absorbed-dose / dose-rate effect for alanine dosimetry,” 16th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards, Gaithersburg, MD, October 2007.

Desrosiers, M. “Irradiation decontamination of postal mail: lessons learned and future opportunities,” IAEA Technical Meeting on Radiation Control of Biohazard Contaminants, Vienna Austria, October 2007.

Desrosiers, M. “Temperature effects in alanine dosimetry,” 15th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards, Gaithersburg, MD, October 2006.

Hudson, L., “Diagnostic spectrometers for high-energy density x-ray sources,” 15th International Conference on Atomic Processes in Plasmas, Gaithersburg, MD, 19 March 2007.

Hudson, L., “X-ray metrology for extreme states of light & matter,” Kansai Photon Science Institute, Japan Atomic Energy Agency, Kyoto, Japan, 6 November 2007.

Hudson, L., “National standards for x-ray and gamma-ray security screening systems,” ComSci08 (Annual Meeting of the Washington Academy of Sciences), Arlington, VA, 29 March 2008.

Hudson, L., “Laser-produced x-ray sources,” Forum on Future Directions in Atomic and Condensed Matter Research, Melbourne, Australia, 22 September 2008.

Minniti R., “Uncertainty analysis in air-kerma measurements from gamma-ray beams using ion chambers,” 52nd Annual Meeting of the Health Physics Society, Portland, OR, 9 July 2007.

Minniti R., “Why Cs-137 irradiators are needed in the United Sates for calibrating instruments,” Nuclear Regulatory Commission, Rockville, MD, 28-30 September, 2008.

Mitch, M., “Model-specific uncertainties in air-kerma-strength measurements of low-energy photon-emitting brachytherapy sources,” 49th Annual Meeting of the American Association of Physicists in Medicine, Minneapolis, MN, July 2007.

Mitch, M., “Measurements of x-ray spectra emergent from low-energy photon-emitting brachytherapy sources,” 50th Annual Meeting of the American Association of Physicists in Medicine, Houston, TX, July 2008.

Seltzer, S., “Fundamental quantities and units for ionizing radiation,” Annual Meeting of the International Commission on Radiation Units and Measurements, Nyon, Switzerland, 22 September 2008.

Soares, C., “Measurements and standards for brachytherapy sources at NIST,” Medical Physics Department Colloquium, Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, 4 December 2007.

Soares, C., “Current status of ANSI/HPS N13.32 revision,” National Dosimetry and Records Conference, Park City, UT, 2 June 2008.

Soares, C., “ANSI/HPS N13.11: status of current update,” National Dosimetry and Records Conference, Park City, UT, 2 June 2008.

Tosh, R., “Uncertainty analysis of spectral methods applied to water calorimetry,” 15th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards, Gaithersburg, MD, Gaithersburg, MD, October 2006.

Tosh, R., “A theoretical study of Boussinesq convection in a water phantom,” 49th Annual Meeting of the American Association of Physicists in Medicine, Minneapolis, MN, July 2007.

Tosh, R., “Study of Boussinesq convection in a water calorimeter for measuring absorbed dose of therapy-level radiation beams,” Comsol Conference, Newton, MA, 5 October 2007.

Tosh, R., “Exposing and correcting systematic errors in a primary reference standard with multiphysics simulations," Comsol Workshop, Gaithersburg, MD, 14 April 2008.

Tosh, R., “Comparison studies of thermistor-based and ultrasonic water calorimeters,” 50th Annual Meeting of the American Association of Physicists in Medicine, Houston, TX, July 2008.