Purpose

The purpose of this procedure is to describe all steps involved in the measurement of air kerma using the four, primary x-ray standard free-air ionization chambers required for the calibration service listed as 46011C [1].

Scope

The calibration and irradiation of instruments that measure x rays are performed in terms of the physical quantity air kerma. The process for establishing calibration coefficients (or factors) for radiation detectors is explained in this procedure. Calibrations are performed by comparing the instrument to a NIST primary standard, which includes four free-air chambers for x rays.

Referenced documents

International Organization for Standardization

ISO/IS 4037-1:1996 X and gamma reference radiations for calibrating dosimeters and dose rate meters and for determining their responses as a function of photon energy--Part 1.: Radiation characteristics and production methods

Consultative Committee for Ionizing Radiation (CCRI)

BIPM, Qualités de rayonnements, Consultative Committee for Ionizing Radiation (CCEMRI) (Section I), 1972, 2, R15.

National Institute of Standards and Technology

NBS Special Publication 250-16 Calibration of X-ray and Gamma-ray Measuring Instruments
NIST Special Publication 250-58 Calibration of X-ray and Gamma-ray Measuring Instruments
NIST Calibration Services Users Guide 1998
NBS Handbook 64 Design of Free-Air Ionization Chambers
NBS Handbook 78 Report of the International Commission on Radiological Units and Measurements
NIST Special Publication 811 Guide for the Use of the International System of Units (SI)
NIST Technical Note 1297 Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurements

Records

Laboratory databooks
Binders
Electronic files

Definitions

air kerma - the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of all electrons liberated by photons in a volume element of air and dm is the mass of air in that volume element. The SI unit of air kerma is the gray (Gy).

beam quality - used to refer to a specific x-ray beam with a characteristic half-value layer and produced by a constant potential kilovoltage.

calibration - the process whereby the response of a dosimeter or measuring instrument is characterized through comparison with an appropriate national standard.

calibration coefficient - the quotient of the air kerma in the absence of the chamber and the charge generated by that radiation in the ionization chamber, expressed in units of Gy/C.

calibration factor - the quotient (dimensionless) of the air kerma or exposure in the absence of the chamber and the electrometer reading with the ionization chamber.

effective energy - the energy of a monoenergetic x-ray beam that has the same half-value layer as the spectrum in question.

exposure - exposure (X) is the quotient of dQ by dm, where dQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons are completely stopped in air of mass dm. The SI unit of exposure is the coulomb per kilogram (C/kg); the special unit of exposure, the roentgen (R), is equal to exactly 2.58E-4 C/kg.

half-value layer - (HVL) the thickness of the specified material added as a beam attenuator that reduces the air-kerma rate by one half of the unattenuated-beam air-kerma-rate value.

homogeneity coefficient - (HC) the ratio of the first to the second half-value layer.

monitor instrument - an instrument used to monitor the stability of the air-kerma rate during an irradiation.

quarter-value layer - (QVL) the thickness of the specified material added as a beam attenuator that reduces the air-kerma rate to one quarter of the unattenuated-beam air-kerma-rate value.

second half-value layer - the difference between the quarter-value layer and the half-value layer.

x-ray unit - system comprised of a high-voltage generator, an x-ray tube and an x-ray controller.

Key words

air kerma; calibration; exposure; free-air chamber; half-value layer; ionization chambers; mammography chamber calibrations; primary standard; standard; uncertainty estimate; x rays.

Background information

The quantity *kerma* characterizes a beam of photons or neutrons in terms of the energy transferred to any material. For the calibration procedures described in this document, consideration is limited to photon beams in air. A complete description of the determination of air kerma and the traceability of the standards is found in sections 4.1, 6.2 and 6.8 of the NIST Special Publication 250-58.

Requirements of instruments to be calibrated

Only ionization chambers known to be stable and reproducible are accepted for calibration in this program. Institutions submitting ionization chambers for calibration are strongly urged to perform stability checks involving redundant measurements in highly reproducible radiation fields before sending their instruments to NIST, and to repeat those checks after NIST calibration, and again at suitable intervals. Instruments submitted for calibration, and material submitted for irradiation, must be shipped in reusable containers.

Explanation of calibration service offered

An x-ray tube produces bremsstrahlung spectra, inhomogeneous beams with photon energies from very low values to a high-energy cutoff given by the maximum potential applied to the x-ray tube. These beams are customarily filtered with a high purity metal to reduce the unwanted low-energy x-rays. Three x-ray calibration ranges are used for the calibration services. Two of the ranges contain x-ray tubes with tungsten anodes. The x-ray beams from these anodes are filtered with aluminum, copper, tin and/or lead. Two anode types are offered for the mammography calibration service, molybdenum (Mo) and rhodium (Rh). The Mo-generated x-ray beams are filtered with Mo, Al, or Rh foils, while the Rh beams are filtered with Rh and Al foils. It is conventional to characterize the "quality" of the filtered x-ray beam in terms of the thickness of aluminum or copper required to reduce the air kerma rate to 50 % and to 25 % of its original value. These thicknesses are called the half-value layer (HVL) and the quarter-value layer (QVL). The HVL and QVL measurements must be made using good-geometry attenuation in order to obtain accurate and reproducible numbers. The second HVL is the difference between the QVL and HVL. The homogeneity coefficient (HC) is the ratio of the first to the second HVL, often expressed as a percent. A HC value near 1 (or 100 %) indicates that the filtration has produced an approximately homogeneous beam that is approaching monoenergetic conditions.

The NIST tungsten x-ray beam qualities are divided into three groups according to filtration, i.e., light (L), moderate (M), and heavy (H) filtration. The beam codes consist of a letter L, M, or H, followed by the generating constant potential in kilovolts. For example, M100 indicates moderate filtration and 100 kV constant potential. The special (S) series beam codes, S60 and S75, have characteristics that are not consistent with those of the L, M, and H groups. The qualities for each group were chosen so that relatively smooth curves result for the graph of tube potential versus HVL. Table 1 gives a complete listing of the NIST beam codes currently available. Depending on the energy response and design of the ionization chamber, the calibration coefficients for a specific ionization chamber often fall on smooth curves when plotted against HVL. In this case, all calibration points have been chosen from a single group, L, M, or H. If calibration points are chosen from more than one group, discontinuities will occur, hence no attempt should be made to interpolate between such calibration factors.

The mammography beam qualities offered at NIST were chosen to cover the range of HVLs of x-ray beams found in clinical settings. The beam codes that name the beam qualities are a combination of the chemical symbol of the anode and the filter respectively, followed by the constant potential in kilovolts. The letter "x" ends the beam codes that name the exit beam qualities. The exit beam qualities, which represent the transmission of the x-rays through the breast, are generated by an additional filtration of 2.0 mm of Al. The mammography beam qualities offered are listed in Table 2.

NIST maintains reference beam qualities from two international organizations, the ISO and the CCEMRI (now known as the CCRI). These beams are generally used for international traceability and measurement comparisons. A list of all ISO beams offered at NIST is found in Table 3a. The NIST H group of qualities agrees with the ISO narrow spectrum (NS) qualities recommended by the ISO document 4037. The NIST M group of qualities is in agreement with the recommendation for radiation therapy calibration in IEC Publication 731. NIST supports the reference CCRI beam qualities, 25 kV and above, described in the CCEMRI/CCRI (1972) document for traceability with the BIPM. The NIST techniques based on these beams are listed in Table 3b.

The selection of beam qualities for instrument calibration depends on the situation of interest. The H qualities are usually used for calibration of radiation-protection instrumentation, as these beams have the narrowest spectrum at each generating potential, and probably most nearly approximate radiation that has penetrated a protective barrier. The M qualities are usually used for calibration of radiation-therapy instruments. The L qualities are predominately for calibration of instruments used for measurement of unfiltered or lightly filtered beams that give high exposure rates, as is often the case in radiation biology and Grenz-ray therapy. The Mo and Rh beam qualities are offered to simulate the clinical mammography beams.

Design philosophy and theory

X-ray calibrations are performed by using the substitution method. Using this method, the air kerma or air-kerma rate is determined at some point in space by a free-air chamber. The instrument to be calibrated is then placed at the same point in space as the standard and the response of the instrument is determined. The calibration coefficient is the quotient of the air kerma, K_{air} in the absence of the chamber, and the charge, Q, generated by that radiation in the ionization chamber:

$$Calibration\ Coefficient = \frac{K_{air}}{Q}$$

The calibration factor is the quotient of the air kerma or exposure, in the absence of the chamber, and the electrometer reading with the ionization chamber:

$$Calibration\ Factor = \frac{K_{air}}{electrometer\ reading}$$

$$Calibration\ Factor = \frac{X}{electrometer\ reading}$$

X-ray range features

Three x-ray calibration ranges are available for instrument calibrations. One range is used for tungsten x rays generated at constant potentials of 10 kV to 100 kV, another is used for tungsten x rays generated at potentials of 50 kV to 300 kV. The mammography x rays are generated at constant potentials of 23 kV to 40 kV. Standardization of x-ray beams for the quantity air kerma or exposure is carried out at NIST by means of four free-air ionization chamber standards. These standards are discussed in Refs. [3, 4, 5 and 6]. Features critical to the proper use of the standards are listed in Table 4. All the standards are shown in Figure 1. Features of the x-ray systems are listed in Table 5.

Special operating procedures for the Attix Chamber

The Attix chamber, a variable-length, cylindrical free-air chamber, differs in design from the other NIST conventional parallel-plate free-air ionization chambers. The differences contribute to its appropriateness as a standard for the measurement of exposure in the mammography energy region. This measurement procedure is based on a subtraction method [7], which involves finding the difference in collected charge for different electrode lengths. The chamber is composed of an aluminum cylinder with a fixed front plate, a variable-position back plate, and an off-center electrode. The cylinder and back plate are positioned with precision stepping-motor controlled slides. For a detailed description of the chamber see Refs. [8 and 9].

The air-kerma determination with the Attix chamber involves the collection of charge with various plate configurations. By changing the volume of the Attix chamber and knowing the corresponding change in length of the collecting electrode, the air kerma can be determined with a minimum of two different plate configurations. Although the minimum number of plate configurations needed to determine the air kerma is two, four measurements are conducted, with the fourth being a repeat of the first position. The electrode length is changed by 5 cm with each plate configuration. The average of the three resulting ratios of the change in charge to change in electrode length is calculated and used in the air-kerma calculation as a component of the mass ionization current. For routine measurements, the defining point of the Attix chamber is positioned at one meter from the focal spot of the x-ray source. Figure 2 shows one possible Attix chamber configuration for a measurement procedure.

Ionization-chamber current-measurement techniques

Ionization currents in air-kerma-standardization measurements are produced by the irradiation of a gas in an ionization chamber. The ionization chamber may be a free-air chamber, such as one of the national standard chambers, or a cavity chamber, where the gas is surrounded by some wall material. Ionization chambers, regardless of type, consist of electrodes that are insulated from one another and are polarized in order to collect charge produced in the gas. The ions produced in the air by the beam are swept from the chamber volume by the electric field between the electrodes. Included in the measurement of these currents are currents not produced by the radiation of interest, but by background radiation and insulator leakage, which is referred to as background current. The magnitude and sign of these extraneous currents must be determined and the measured current corrected for their effects in order to determine the true ionization current. The importance of the correction for background and leakage is, of course, relative to the magnitude of the ionization current, but good measurement technique requires, prior to attempting radiation measurements, that the background currents be determined. As a rule of thumb, and without taking special precautions, the background current for a good-quality ionization chamber should be less than 5 fA. The measurement of background currents will also include currents due to background radiation, so the environment and special circumstances must be considered in evaluating data. For example, if tests are made on a large-volume ionization chamber in a background environment found suitable for small-volume chambers, the extra sensitivity of the large chamber requires separate evaluation of the background environment. Keithley 617 and 6512 electrometers are used to measure the charge collected in the ionization chambers.

X-ray calibration data-acquisition system

Data are acquired for x-ray standardization by measurement of all conditions relevant to establishing the x-ray air-kerma rate at a particular distance from the x-ray-tube target. The data acquired consists of data for the computation of ionization currents, parameter data, and measurement-system test and information data. Data used to determine the ionization currents includes the electrometer charge measurements, the atmospheric pressure and pertinent air temperatures, and the shutter-open time interval. The parameter data includes the x-ray tube current and potential, the x-ray tube target-to-reference-point distance, and the beam-defining filter thickness and the diaphragm diameters. Test data includes the measurements of the collection potentials on the standard free-air chamber, the monitor chamber, and the chamber being calibrated, if appropriate. All data are acquired through National Instrument's LabVIEW interfacing. The required equipment is listed in Table 6 and Table 7.

Equipment

The temperature probes, pressure transducers and electrometers are considered essential support equipment to allow routine calibrations of ionization chambers. The maintenance and calibration of this support equipment follows. The quality of the ionization chamber calibration is not monitored by the calibration of the support equipment but rather by the NIST artifact quality procedure. The quality check of the calibration of all customer ionization chambers is determined by the reproducibility of the calibration coefficients of the NIST test chamber. Therefore, if a calibration coefficient does not reproduce, the performance and calibration of the support equipment would be investigated.

The temperature sensors in the 100 kV and 300 kV x-ray ranges are Hart Scientific platinum resistance thermometers used to measure room, free-air chamber, and monitor-air temperatures. In the Mammography Facility, the Hart 5613 platinum resistance thermometers and Hart 1502 digital thermometers are used for air-temperature measurements in the vicinity of the Attix free-air chamber, the monitor chamber and the test chambers. The thermometer calibration correction is applied internally to the 1502 digital meters.

The atmospheric pressure for the 100 kV and 300 kV x-ray ranges is measured by the Setra digital barometer, powered by a NIST power supply serial no. 2561. The output voltage is calibrated for pressure measurements in units of millimeters of Hg. A conversion to the unit of pascal is applied in the calculation of the calibration factor. The equation used for computing the pressure is:

$$P(mmHg) = -3.483 + 94.336(voltage)$$

In the mammography range, a Setra 370 barometer is interfaced through RS232 to the data-acquisition software. Any necessary correction is applied directly through software as part of the air-kerma calculation.

Two customized voltage dividers were manufactured for the purpose of voltage calibration of the x-ray generators used in the three calibration ranges. Both dividers were initially calibrated by the NIST Electricity group. These dividers are periodically used for routine calibrations. A check of the voltage calibration is required after any of the x-ray generators are changed due to maintenance or replacement. The dividers must be directly placed in series with the generator cables into the x-ray tube and require a knowledgeable, experienced person for installation. A high precision voltage meter must be used to read each divider. This equipment is listed in Table 6.

All time signals are controlled by a National Instruments data-acquisition card, which contains two 24-bit, 20 MHz counters/timers. The signal to the timers is a pulse produced by a photodiode when its light beam is interrupted by a flag on the shutter mechanism. Upon initiating the exposure, counting commences only on receipt of the photodiode pulse. At the end of the preset time interval, the shutter is caused to close but the clock continues to count until the edge of the shutter crosses the portal mid-point. The timing shutter operation in both the 100 kV and the 300 kV x-ray ranges has recently been modified to use air-cylinder-controlled solenoids. The 300 kV machine also has a safety shutter that opens before, and closes after, the timing shutter. The lead thickness in the timing shutter was minimized for mechanical purposes but is of sufficient thickness to prevent significant effects on instrument readings in the interval between operations of the two shutters.

The charge measurements are acquired through the use of Keithley 617, 617-HiQ and 6512 electrometers. The internal capacitors of the electrometers are calibrated upon introduction into the system and any time the charge collection is suspect. Any necessary correction is applied as part of the air-kerma calculation in the Labview software. Keithley electrometers, models 6512 and 617-HiQ, are maintained for use in the low- and high-energy ranges. Four electrometers are maintained in the mammography range, two standard-capacitance-range electrometers (20 nC), a 617 HIQ (20 μC), and a midrange 617 (200 nC); the 6512 can be used as a substitute for the 617. The HiQ is dedicated for use if a monitor chamber is required, and the midrange 617 is used for collecting charge on the Attix chamber but the 6512 can be used as a replacement, as long as the time of the exposure is controlled so the collected charge does not overload the electrometer, producing an error. The two 20 nC capacitance range electrometers are used for the customer chambers. The procedure of calibrating a NIST reference-class chamber with each customer chamber is a quality-assurance check that rules out electrometer malfunctions.

Support equipment calibrations

There are no specified calibration intervals for the critical support equipment because the equipment is calibrated using the in-house reference standards described below any time there is a question of reproducibility of the NIST transfer ionization chamber. Since the QA procedure for all x-ray calibrations requires the calibration of a NIST ionization chamber, any change in the reproducibility above 0.3 % to 0.5 %, depending on the chamber type, may require an investigation into the support equipment used for the calibration. If any of the critical support equipment is found to be out of calibration or damaged, it would be removed and its condition clearly marked. A calibrated, identical model replacement instrument would be used for calibrations to continue and the instrument would be clearly identified on the Access equipment log in the data acquisition software, which serves as the instrument log for calibrations. If appropriate, damaged and repaired critical support equipment should be recorded in the current databook for the calibration of support equipment, entitled *Calibration of Auxiliary Equipment* Number 914, located in B019; the tracking of all equipment used for calibrations is performed by the Labview data acquisition system and stored in Access log sheets. All calibration records for the critical support equipment are located in a file drawer in B033. In-house calibration records for the barometers and thermometers are maintained in electronic files in the folder named *supportequipqa* located on the group server in the *OBRIEN* folder.

Capacitor calibrations

Periodically since 1956, the reference capacitors are submitted to the NIST for primary calibration. The capacitors have nominal capacitance values of 100 pF, 1000 pF, 10 000 pF and 100 000 pF. Some typical long-term calibration results have an uncertainty stated by the Electromagnetics Division of no more than ± 0.05 %. The uncertainty is interpreted by the Electromagnetics Division as equivalent to three standard deviations. Typical reproducibility for over more than forty years is 0.02 %. Capacitors are available for use with the electrometer calibration test for periodic instrument checks. The electrometer calibration test is described in the section labeled, *Test of high-quality electrometers*, of this procedure.

Temperature indicator calibrations

Two liquid-in-glass thermometers had been previously calibrated and used as “in-house” reference standards. Due to the safety guidelines to retire and remove from use the mercury filled thermometers, an electronic meter and probe has been identified as a replacement. One liquid-in-glass thermometer will be kept, but will no longer be calibrated. It will be stored for possible use in resolving any measurement discrepancies. A Fluke/Hart meter 1504 (sn A95694) with probe model 5610-5 SNA932006 was acquired and serves as the “in-house” temperature reference standard for x- and gamma-ray calibrations. The meter/probe will continue to be calibrated periodically as necessary to the NIST primary standard. Various probe and meter combinations are periodically directly calibrated by the NIST temperature experts.

Pressure indicator calibrations

An aneroid barometer, Wallace and Tierman, Model FA 139, Serial Number XX11242, and other laboratory reference barometers have direct NIST traceability. Calibrations of individual pressure indicators used at the various sources are made by placing the calibrated barometer alongside the instrument to be tested and connecting both to a variable-pressure device. The instrument readings are compared over a range of pressures that is somewhat larger than normally expected. Data is taken with increasing and with decreasing pressure. The comparisons are made directly or through voltage signals. A correction factor is obtained from this data for each pressure indicator, if required. This calibration procedure is conducted periodically and checks are made when the pressure rises or falls to extremes.

Procedures

Administrative procedures

Customers request calibration services in a variety of ways. Typically, a new or first-time customer will establish contact with the Dosimetry Group by email, requesting information regarding techniques offered, charges, turnaround time, and shipping information. At this stage, there is generally an opportunity to discuss with the prospective customer the type of service being requested and methods of shipment to reduce the risk of damage. The customer is informed of the administrative procedures for acceptance of the requested work as outlined in the NIST QMI and in the RPD QMII, in accordance with the NIST calibration policy. In addition to completing the NIST payment authorization requirements, the customer must include a detailed description of the calibration request, instrument model and serial numbers, name and telephone number of a technical contact, the official address which will appear on the calibration report, the return shipping instructions including the address, any special handling requirements, the specified mail carrier with account number for payment, the value of the equipment, and instructions for the insurance amount, if any. The customer is directed to the complete instructions and policies for calibrations on the NIST calibration ordering webpage. The Calibration Information request form, see Table 8, can be completed by the NIST technical contact as a method to organize the dates and information about the calibration request. The NIST order number is generated by the NIST online ordering system upon completion of the NIST policy for payment documentation. At the completion of the calibration, a copy of the purchase order, the final copy of the calibration report, the calibration raw data, summary sheets, a copy of the final fee sheet and any documents of correspondence concerning the calibration are maintained in the customer's calibration report folder filed by the unique dosimetry group (DG) number.

When instruments arrive for calibration, they are unpacked and inspected for damage. Special attention is given to the condition and type of connector. If an adaptor is sent with the chamber, this should be noted on the inventory list along with the description of the chamber. Shipping damage is reported to the NIST shipping department. If an instrument arrives in a state of disrepair that is obvious by visual inspection, the customer would be notified and the instrument returned without calibration. The instrument would be rejected if the window is obviously dented or punctured or if the chamber cable is damaged. If the shipping box is visually damaged, this should be noted and the customer consulted.

After the instrument is calibrated, the calibration report is generated. Templates generated in Microsoft Word and Excel are available to simplify this procedure and to ensure consistency in the reporting format. The reports are printed on official NIST letterhead. A sample report is found in Appendix 1. Upon completion of the requested calibration, the final calibration report is reviewed and initialed by the preparer, the reviewer, the Group Leader and the Division Chief. A photocopy of the report is maintained in the customer's DG folder located in room B033 of building 245 and the original is sent to the customer within the container of the returned equipment, or by mail if requested by the customer. The instrument(s) is(are) then repackaged in the original container, or a more suitable one, for return shipping. A shipping form is prepared by the Group Secretary or the shipping page of the NIST online ordering system is printed and attached to the box. The NIST shipping department collects the box from the Group Secretary's office in building 245.

X-ray calibrations

X-ray calibrations are performed using the substitution method: the standard is used to measure the air-kerma rate at a given point; the instrument to be calibrated is placed at that point and exposed to the same calibrated x-ray source under the same conditions. The probe's response is normalized to 101.325 kPa (760 mmHg) pressure and 295.15 K (22 °C) if the instrument is open to the atmosphere, which depends on the type of chamber.

Environmental parameters

During all calibrations, the laboratory temperature must be maintained between 22 °C +/- 2 °C and stable to +/- 0.1 °C for typical measurement sets of 10 minutes. If the temperature is not stable during a typical measurement set, calibrations should be postponed. The laboratory humidity should be maintained between 20 % to 50 % relative humidity. Since the pressure is monitored and the charge data is normalized to pressure, it is good laboratory practice to postpone data collection and calibration work during sudden changes in pressure due to storms or weather fronts. If the pressure reading is stable during the calibration collection time, the measurements can continue. The pressure should be monitored and the influence on the normalization factor should be considered.

Set-up procedure

Prior to calibration, the test chamber is first aligned in the x-ray beam. The cross-hair reticle of a telemicroscope is set to the defining plane of the appropriate free-air chamber prior to final alignment of the probe; see Figures 1 and 3. For the Wyckoff-Attix (50 kV to 300 kV) chamber, the defining plane is the white line on the aperture holder. For the Ritz (20 kV to 100 kV) chamber, the defining plane is exactly 15.00 mm beyond the white line on the aperture holder in the downstream direction from the x-ray source. For the Lamperti (10 kV to 20 kV) chamber, which has been dedicated to electronic brachytherapy calibrations, located in B24 but could still be used in the x-ray facility if needed, the defining plane is exactly 20.00 mm downstream from the source from the scribed line on the plastic insert that fits into the removable shield and touches the front face of the aperture. For the Attix (10 kV to 50 kV) chamber, the defining plane is the scribed line in the brass aperture holder. The test chamber is placed in a holder and the laser beam is used to determine vertical and horizontal alignment. Adjustment of the test chamber position to the defining plane is accomplished by sighting through the telemicroscope that was previously aligned on the defining plane of the free-air chamber. Motorized slides are then used to adjust the test-chamber reference point to the standard defining plane. Control of the motorized slides is accomplished using a control box located in the vicinity of each telemicroscope. In general, all chambers should be aligned to the center of the test-chamber volume, but this should be verified with the customer. Most chambers are mounted perpendicular to the beam axis. If the chamber has a window, then it should be mounted such that the window faces the x-ray source. If a chamber has a reference line, then it should be used for alignment purposes. An identification mark or serial number should be used to reference the rotation with respect to the x-ray source. The alignment conditions, orientation and rotation of the chamber should be recorded in the calibration report.

If the chamber diameter is larger than 10 cm, such as the Exradin A6 chamber, the exact chamber diameter must be measured using a micrometer. The radius should be calculated and added to the previously determined scale reading of the telemicroscope. The cross-hair reticle of the telemicroscope should be moved to this location and be used as the tangent alignment point of the large-diameter chamber. The measured diameter should be recorded for future use. A further consideration for x-ray calibrations is the choice of an appropriate beam size. For this purpose, a parameter called the "beam size" is compared to the largest dimension of the active volume of the chamber. The general practice is to use a beam size that is only a few centimeters larger than the active-volume size so as to minimize irradiation of inappropriate volumes in the probe stem. For x rays, as opposed to high-energy gamma rays, this is of secondary importance because the chamber stem attenuates the radiation considerably. The beam size of the x-ray beams, for all beam-defining apertures for the vertical and horizontal beam positions, has been determined using an Exradin A1 ion chamber, as well as film. The useful beam size is the point where the ratio of the optical density to the center of the film reveals a change of less than 0.5 percent. The ratio of the intensity as measured with the ion chamber of the center to the outer point of the useful beam should also change less than 0.5 percent. Table 9 lists all the possible beam sizes for each calibration range.

After a pre-irradiation, background current measurements are taken prior to calibration. If the background current is a significant fraction of the expected exposure reading, either the probe is cleaned or is not calibrated. In addition, background current measurements are made at the time of calibration. Again, if the background current is found to be a significant fraction of the expected reading, the insulators are cleaned using canned dry gas. Because the gas is cold due to expansion, time must be allowed for the chamber to equilibrate with room temperature. If the cleaning procedure is not successful, the calibration is terminated.

After mounting and aligning the chamber in the holder and applying the appropriate collection potential requested by the customer, the collecting voltage is checked at the chamber. This insures that the voltage connection has been made. Certain triax-to-BNC adapters can accidentally ground and a short circuit occurs if the triaxial portion of the adapter, which is held at high voltage, is not insulated; see Figure 4. It is good practice to insulate this adapter and secure it in place so that movement of the instrument does not cause the cable to move. It is also important to keep all connections out of the radiation beam.

For all customer calibrations, a NIST reference-class transfer ionization chamber is calibrated for quality assurance. Some typical chambers are shown in Figure 4. Generally the NIST chamber selected is similar in design or collection volume to the customer chamber being calibrated. A NIST chamber is selected which has a previous calibration history to the reference radiation qualities which were selected by the customer. It is customary for the NIST chamber to be mounted in the holder closest to the NIST primary standard. The NIST reference-class chamber is aligned the same way as described previously for the customer test chamber.

Procedures for the calibration of chambers and collection of data

The following procedures are listed in numerical order. The actual order in which the steps are completed is required only where noted.

100 kV or 300 kV x-ray calibration range

1. Turn on main power. The 100 kV main power is located on the wall behind the main computer control console. The 300 kV main power is located on the wall in the 300 kV range.

2. Turn on water supply and return. Failure to turn on water will result in an interlock error.

3. Turn on power to motor drives mounted in each range; see Figure 5.

4. Warm-up x-ray tube of choice.
    a. turn on Pantak unit with key to position three; see Figure 6.
    b. press blue “enter” key on the Pantak PMC controller and follow directions on digital entry pad
    c. press green “start” key to begin preprogrammed warm-up, which takes about 20 minutes
    d. if the unit has not been warmed-up for two weeks, follow the manual extended warm-up

5. After the completion of the warm-up, to activate the remote mode on the Pantak PMC controller turn the Pantak key off and then back on to position three.
    a. after the “testing please wait” message press the blue “escape” key
    b. at the “enter password” prompt, enter 7318 and press “enter”
    c. press “enter” to continue until the prompt asks if remote control is desired
    d. press “prog” as directed by the prompt to set unit in the remote mode
    e. press enter as directed and eventually “escape” to leave the setup mode
    f. the display should read “remote mode active”

6. Turn on the computer. The power on the Hopewell Design Inc. (HDI) controller (see Figure 7) must be off prior to putting power on the computer, and the power to the HDI controller must be off prior to shut down of the computer. The correct x-ray range must be selected and all connections made for that range.

7. Turn on the HDI controller using the key on the front panel

8. Data entry in Access
    a. start Access and use C:\100-300 XRay Sys\100300 NIST Track Rev7.2
    b. select the form tab

c. select the switchboard option
d. enter appropriate data under the customer, instrument and work order options

9. Start the HDI LabVIEW software using the provided shortcut for Rev8a.vi
   a. login by entering operator's initials (CMO) and the configuration code (456)
   b. select the range to use. The default is the 300 kV range; for the 100 kV range, click on the pink "300 x-ray system" selector key in the upper right of the front panel HDI software to toggle to the blue 100 kV system
   c. home everything. For the 300 kV range, select only the device under test (DUT) first and then each of the other options individually upon the completion of motion of the previous. All options can be selected and homed simultaneously for the 100 kV range.

10. Secure chamber cart in the desired position.

11. Mount chambers as described previously using the laser and telescope. Connect signal and high-voltage cables; see Figure 4. Toggle between chambers using the front control panel; press actuate to move the chambers.

12. Verify that the correct filter wheel is mounted; if not then repeat the homing procedure of the filter wheel and verify that the filter corresponds to the selection. If an M-series beam is being used in the 300 kV range, add the additional M-filtration which is controlled by a switch located on the main control panel.

13. Verify that the correct cables are connected on the front control panel for the chamber signals and high-voltage and that all support equipment to be used is energized; see Figures 7, 8 and 9.

14. All addresses for the IEEE equipment should never be changed, but, if necessary, verification of the appropriate address can be made. All addresses are on labels on the control panel.

15. Once the chambers are positioned and secured, apply high voltage. Enter the desired high voltage on the front panel display of the HDI software and flip the Bertan HV switch on. The voltage is maintained on the primary standards, but make a visual check that voltage is set; see Figure 8.

16. Close doors to ranges so the safety interlocks will allow the use of the x-ray beam.

17. Verify that the HDI software is communicating with the Pantak controller
   a. select computer mode on front panel
   b. enter kV and mA
   c. turn on HV control toggle
   d. select a beam code to initiate response with controller
   e. check background current on chamber

18. Verify the collection time so as to not overload the electrometers. This depends on the air-kerma rate for the beam quality. Put each chamber in the beam using the conditions for the calibration and establish the collection time. Press the "exposure enable" at the bottom of the screen so it is not red.

Secure the interlocks for entrance to the rooms. Press the red “open” button on the HDI control panel to open the shutter. The time of the exposure will accumulate on the front panel of the HDI software.

19. Press “build sequence” to prepare an automated test sequence.

20. Enter the work order number of the previously entered data in Access. When the “get work order” button is selected, the background information for the customer chamber automatically is entered. The toggle switch for the customer chamber position (T1 or T2) must correspond to the correct position.

21. Create a unique cal run ID.

22. Enter the pressure, temperature and humidity from the front-panel displays.

23. Enter the beam aperture selected, the diameter of the beam, and the distance of the calibration.

24. Enter the identification information of the NIST reference-class chamber to be calibrated.

25. Enter the desired collection times and the number of measurements to be collected.

26. Finally, select the beam codes, enter the currents and select the ISO Al filter if appropriate.

27. Upon completion, press “build sequence”.

28. At the front panel press “start auto sequence” to begin the calibration.

29. Upon completion of the calibration, review the data from the printed reports. If some data needs to be eliminated go to Access.
    a. open the “exphist” table and find the data points to delete. Place a check in the appropriate column to delete the data point.
    b. on the front panel of the HDI software select “Redo Report”. Enter the work order number and the unique cal run ID. Press “get records”. Select the appropriate beam code. Repeat until all data is recalculated.

30. A summary of the final data for both chambers is stored to an Access file named InstCalReport. Select the records desired and copy to an Excel spreadsheet to complete the summary calculations. The spreadsheet should be named by the DG number and stored in the locations as described below.

31. Repeat steps 28 through 30 until a sufficient number of calibrations have been completed for each beam quality.

32. The expected standard deviation on the calibration results depends on the chamber type but, generally, a standard deviation near 0.1 % is acceptable.

33. The averages of multiple calibrations are maintained in the Excel spreadsheets. These Excel files are named by the DG number and saved as described in the electronic-data section of this manual.

34. The data is also recorded on index card forms that have been maintained for many years for all previously calibrated chambers. The current calibration results are compared with previous results. This verifies the quality of the calibration.

35. The summary data is then pasted into the Word or Excel templates for the calibration report. A sample report follows in Appendix 1.

Mammography x-ray calibration range

1. Turn on main power which is on the wall inside the calibration facility. The water cooler will automatically be energized.

2. Turn on water supply and return. Failure to turn on water will result in an interlock error.

3. Turn on power to motor drives mounted on back of tube stand. This power generally remains energized.

4. Verify that the Velmex controller, which is under the primary standard, is energized.

5. Energize alignment laser, located in back of range.

6. Verify that the primary standard cart is secured at 1 m and that the Attix chamber's moveable alignment slide is in the position furthest from the source; see Figure 10.

7. First verify that the HDI controller key switch is off, then energize the computer; see Figure 11.

8. Turn key to the third position on the MP1 x-ray controller.

9. Turn key switch to "on" at the HDI controller.

10. Select x-ray tube by key located above the MP1 controller.

11. Verify that power is on to all instruments visible from the control area. These include four Keithley electrometers, four Bertan high-voltage supplies, three Hart thermometers and a Setra barometer. The front panels of these instruments should be illuminated; see Figure 12.

12. Start the HDI LabVIEW software using the provided shortcut for Rev8a.vi
    a. login by entering the operator's initials (CMO) and the configuration code (456)
    b. home all instruments
    c. select the appropriate tube, close the tube shield, and then select actuate to position the tube
    d. home the Velmex controller by selecting the "home" button by the FAC position selectors

13. With the shielding-door closed (so the interlocks are connected), perform a test of the shutter. With the expose enable off, press the open button on the HDI controller. Press the close button to close the

shutter. This test must occur prior to the first automated calibration to ensure proper performance of the shutter.

14. Warm-up the x-ray tube. The MP1 controller must be in mode 101 to warm up the Rh tube and 004 mode to warm up the Mo tube. For complete details see the MP1 manuals. Once the 20 minute warm-up is complete, select the 800 remote operating mode to operate the Rh tube and 004 manual mode to operate the Mo tube.

15. Verify that computer communication has been made with the x-ray controller by selecting a different beam code. Verify that the kV changes on the display window.

16. Mount chambers using the laser and telescope starting with the Attix chamber and then follow with chambers T2 and T1. Connect signal and high-voltage cables. Toggle between chambers using the front control panel: press actuate to move the chambers.

17. All addresses for the IEEE equipment should never be changed but, if necessary, verification of the appropriate address can be made. All addresses are on labels on the control panel.

18. Once the chambers are positioned and secured, apply high voltage. Enter the desired high voltage on the front panel display of the HDI software and flip the Bertan HV switch on. The voltage is maintained on the primary standards, but make a visual check that voltage is set.

19. Close door to range so that the safety interlocks will allow the opening of the x-ray shutter.

20. Data entry in Access
    a. start Access using the shortcut on desktop for Mamsys NIST Track Rev7.2
    b. select forms
    c. select switchboard
    d. enter appropriate data under the customer, instrument and work order forms

21. Verify the collection time, so as to not overload the electrometers. This depends on the air-kerma rate for the beam quality. Put each chamber in the beam using the conditions for the calibration and establish the collection time. Press the “exposure enable” at the bottom of the screen so it is not red. Secure the interlocks for entrance to the rooms. Press the red “open” button on the HDI control panel to open the shutter. The time of the exposure will accumulate on the front panel of the HDI software.

22. Press “build sequence” to prepare an automated test sequence.

23. Enter the work order number of the previously entered data in Access. When the “get work order” button is selected, the background information for the customer chamber automatically is entered. The toggle switch for the customer chamber position (T1 or T2) must correspond to the correct position.

24. Create a unique cal run ID.

25. Enter the pressure, temperature and humidity from the front-panel displays.

26. Enter the beam aperture selected, the diameter of the beam, and the distance of the calibration.

27. Enter the identification information of the NIST reference-class chamber to be calibrated.

28. Enter the desired collection times and the number of measurements to be collected.

29. Finally, select the beam codes.

30. Upon completion, press “build sequence”.

31. At the front panel press “start auto sequence” to begin the calibration.

32. Upon completion of the calibration, review the data from the printed reports. If some data needs to be eliminated, go to Access.

a. open the “exphist” table and find the data points to delete. Place a check in the appropriate column to delete the data point.

b. on the front panel of the HDI software select “Redo Report”. Enter the work order number and the unique cal run ID. Press “get records”. Select the appropriate beam code. Repeat until all data is recalculated.

33. A summary of the final data for both chambers is stored to an Access file named InstCalReport. Select the records desired and copy to an Excel spreadsheet to complete summary calculations. The spreadsheet should be named by the DG number and stored as described in the electronic-data section of this manual.

34. Repeat steps 30 through 33 until a sufficient number of calibrations have been completed for each beam quality.

35. The expected standard deviation on the calibration results depends on the chamber type but generally a standard deviation less than 0.5 % is acceptable.

36. The averages of multiple calibrations are maintained in the Excel spreadsheets. These Excel files are named by the DG number and saved as described in the electronic-data section of this manual.

37. The data is also recorded on index card forms that have been maintained for many years for all previously calibrated chambers. The current calibration results are compared with previous results. This verifies the quality of the calibration.

38. The summary data is then pasted into the Word or Excel templates for the calibration report. A sample report follows in Appendix 1.

Electronic data

All data collected with the NIST reference-class chambers is saved in the appropriate files located in the group server in the *x-ray/chamberhistory* folder. The folder to be used is either *NISTREFSTD* or *NISTREFSTDMAMMO*, depending on which type of chamber is used. The files are organized and named by model and serial number. The calibration history for many NIST reference chambers obtained prior to 1999 is maintained in binders located in room B019.
Similarly, the data collected using the customer chamber and the associated files and the final calibration report is saved in the group server*:* *x-ray/calibrationreports/allcustomerdata*.

In-house calibration checks and traceability

The long-term reliability of NIST dosimetry calibrations depends on the stability of the NIST air-kerma standards. For x rays, the NIST air-kerma standard is the response of the appropriate free-air chamber. The four free-air chambers are also periodically compared. The in-house calibration checks are intended to check both the stability of the NIST standards and the reliability of the calibration procedures. Comparison results are listed in Ref. 6 and in published reports. References 10-20 are recently published comparisons which establish and demonstrate traceability of air kerma.

Two methods are used to verify a calibration. The first is to calibrate a NIST chamber that has a calibration history and is similar to the customer's chamber as described previously. The second check is an examination of previous calibrations of the customer's instrument at the same beam quality. If the discrepancy is significant, greater than 0.5 % but dependent on the chamber type, an investigation is warranted. If there are several previous calibrations of the customer's instrument at any one beam quality, one can estimate the reproducibility and decide whether the current value is acceptable. Any discrepancy found for a NIST check chamber of the order of magnitude mentioned above gives rise to a thorough investigation of the calibration procedure. Alignment, temperature indications, distance, etc. are to be checked again. If the discrepancy cannot be resolved, the complete calibration process is repeated.

Test of high-quality electrometers

NIST uses high-quality feedback electrometers with current-type ionization chambers. When the calibration of an electrometer is required, the following procedure is used. The procedure involves electrically testing the electrometer using a feedback capacitor and computing a calibration factor, C_Q.

Procedure for test of high-quality feedback electrometers

1. This procedure describes the calibration of a Keithley 617 or 6512 electrometer, but may be applied to other electrometers if proper adjustments are made to setup and operational parameters.

2. Required equipment is located in B033
    a. Fluke model 343A DC voltage calibrator
    b. 1000 pF +/- 0.1 % standard air capacitor
    c. Low-noise coaxial BNC cable
    d. Keithley 6147 coaxial/triaxial adapter

3. Ensure that the voltage calibrator has been calibrated recently with the calibrated Hewlett Packard digital voltmeter model 3456A.

4. Connect the voltage source to the capacitor using the coaxial cable as shown in Figure 13.

5. A Keithley 6147 adapter is required on the input BNC on the back of the electrometer.

6. Connect the capacitor to the 6147 on the electrometer using the low noise cable.

7. Apply power to the electrometer. The electrometer should have power on it for at least two hours prior to use.

8. Turn on the voltage source, which should be on for about 30 minutes prior to performing a calibration.

9. Set the zero check on the electrometer to ON.

10. Set the range setting to the setting most likely to be used during normal operation and record this setting.

11. Set the electrometer to the Coulombs mode.

12. Turn the V, Ω guard switch on the back of the electrometer to the OFF position for this charge calibration.

13. Turn the zero check OFF and record the initial reading.

14. Apply the desired reading and record this final reading.

15. Turn the zero check ON and adjust the voltage source to 0.

16. Repeat the above procedure using both polarities until the desired amount of data is collected.
    a. take the appropriate number of measurements for each setting depending on the stability of the readings
    b. to change the polarity, reverse the connectors to the voltage source

17. Multiply the voltage setting by the capacitance to obtain the standard charge. If a voltage-source correction factor is available, multiply this by the standard charge.

18. Subtract the initial reading from the final reading to obtain the net charge.

19. Average the net charges if more than one reading was collected for a given voltage.

20. Calculate the calibration factor (C_Q) by dividing the standard charge by the net charge. The electrometer measurements should be corrected by C_Q, which was determined by applying a known charge to the electrometer input and observing the corresponding charge reading.

Uncertainty Analysis

The method of uncertainty assessment follows the NIST policy of expressing uncertainty, as outlined in the NIST Technical Note 1297. Conventional statistical estimates are given as standard deviations of the mean, and are designated as “Type A”, which can be considered to be objective estimates. All other uncertainty estimates, which are designated “Type B”, are subjective estimates, based on extensive experience. The “Type B” uncertainties are estimated so as to correspond to approximately one standard deviation. The Type A and Type B estimates are combined according to the usual rule for combining standard deviations, by taking the square root of the sum of the squares (i.e., the quadratic sum). The quadratic sum of the two types of uncertainty is then considered to be the combined standard uncertainty, which is in turn multiplied by a coverage factor of two (k=2) to give the expanded uncertainty. This expanded uncertainty is considered to have the approximate significance of a 95 % confidence limit. Table 10 lists the details of the assessment of uncertainty for the air-kerma rates determined for the tungsten x-ray beams by the free-air ionization chambers. Table 11 lists the details of the assessment of uncertainty in the calibration of a typical ionization chamber. Table 12 lists the details of the assessment of uncertainty in air-kerma rates determined for the mammography x-ray beams by the Attix chamber. Table 13 lists the uncertainty components for the calibration of instruments used for mammography. As the estimate of uncertainty varies lightly with beam qualities, methods of measurement, and rate, in each case the largest value is used for the estimate. In an official calibration, measurements could be repeated to maintain optimal conditions.

Safety

The main safety consideration is radiation protection. As described below, every effort is made to avoid any possibility of radiation exposure, even though it would be highly unlikely that serious exposures could occur accidentally. Another safety consideration is exposure to high voltage, such as exists on ionization chambers and standard chambers during calibration. There is no danger of high voltage related to the x-ray generators because the equipment now in use has no exposed high voltage in a normal operating mode. All radiation areas in the building are marked with striped tape and dosimeters must be worn by all personnel. Radiation safety training and assessment services are provided by the NIST Gaithersburg Radiation Safety Division.

Radiation safety

First and foremost, the three x-ray source ranges are designed to eliminate any possible exposure to x radiation. Details are listed in the safety protocols posted in each calibration range. The 100 kV x-ray tube is interlocked with its power supply in such a way that if the tube is moved from a safe position, i.e., away from a lead shutter, the high voltage is turned off. Flashing red lights signal any malfunction to the shutter, and an audible area radiation detector has been recently implemented as a back-up precaution. The 300 kV x-ray tube is enclosed in a housing of 19 mm Pb and 6.4 mm steel. There is a 25 mm lead safety shutter and a 12.7 mm lead timing shutter in front of the beam portal. Both x-ray calibration ranges are protected by lead-lined doors that are interlocked in a fail-safe manner with the shutters. This means that the shutter or shutters cannot be opened if the door interlock is open. Where no door exits, as in one area of the 300 kV x-ray range, a light beam is used for protection. A radiation rope is also used to draw attention to all the posted signs. In addition, a time-delay device inside the 300 kV x-ray range must be actuated upon leaving or the shutter cannot be opened. As a further indication of radiation danger, two red lights are turned on whenever the shutter or shutters are open. A flashing red light associated with the 300 kV x-ray set indicates that high voltage is on the x-ray tube. The mammography-range shielding door is interlocked with the x-ray tube shutter. If the door is opened or is not fully closed, the shutter will return to the shielded position. An audible alarm will sound if the shutter is not fully closed. Red lights illuminate when the shutter is open. Additional lead shielding surrounds the x-ray tube, which must be in the shielding position for power to be applied to the x-ray tube. No area radiation monitor is used due to the extremely narrow beam and the low-scatter conditions resulting from the low-energy x rays used in the mammography range.

High-voltage safety

The only danger that exists from high voltage comes from the free-air ionization chambers, the customer chamber, and the x-ray-calibration-range monitor chambers. To prevent dangerous electric shock, almost all power supplies contain current-limiting resistors in the high-voltage circuit. Common sense is dictated when working around ionization chambers that have exposed high-voltage electrodes. Appropriate warning signs are posted. The risk of high voltage from the Attix chamber is minimized by surrounding the chamber with its protective cover.

Filing and Retention

The Radiation Physics Division (RPD) Quality Manager shall maintain the original and all past versions of this RPD Procedure.

Table 1. NIST Calibration Conditions for X-Ray Measuring Instruments

NIST Calibration Conditions for X-Ray Measuring Instruments

Beam code	Additional filtration [a]				Half-value layer[b] (HVL)		Homogeneity coefficient (HC)		Effective energy (keV)
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al	Cu	
X-Ray Beam Qualities									
L10					0.037		86		
L15					0.059		70		
L20					0.070		72		
L30	0.30				0.23		60		
L40	0.53				0.52		61		
L50	0.71				0.79		63		
L80	1.45				1.81		56		
L100	1.98				2.80		58		
M20	0.27				0.15		72		
M30	0.5				0.36		65		
M40	0.89				0.74		67		
M50	1.07				1.04		68		
M60	1.81				1.68	0.052	63	60	
M80	2.86				3.08	0.1	67	61	
M100	5.25				5.10	0.2	74	55	
M120	7.12				6.77	0.31	76	53	
M150	5.25	0.25			10.30	0.66	86	63	
M200	4.35	1.12			14.73	1.64	94	68	
M250	5.25	3.2			18.49	3.2	98	85	
M300	4.25		6.5		21.77	5.3	99	97	
H10	0.105				0.051		77		
H15	0.5				0.16		87		
H20	1.01				0.36		89		
H30	4.50				1.2		86		
H40	4.53	0.26			2.93		94		
H50	4.0			0.1	4.16	0.14	92	93	38
H60	4.0	0.61			6.06	0.25	92	94	46
H100	4.0	5.2			13.51	1.15	98	92	80
H150	4.0	4.0	1.51		16.93	2.43	99	96	120
H200	4.0	0.6	4.16	0.77	19.72	4.1	99	99	166
H250	4.0	0.6	1.04	2.72	21.59	5.19	99	98	211
H300	4.1		3.0	5.0	23.55	6.19	98	98	252
S60	4.35				2.81	0.09	74	66	
S75	1.50				1.81		58		

[a]The additional filtration value does not include the inherent filtration. The inherent filtration is approximately 1.0 mm Be for beam codes L10-L100, M20-M50, H10-H40 and S75; and 3.0 mm Be for beam codes M60-M300, H50-H300 and S60.[b]The x-ray tubes were installed in 2008 and 2015.

Table 2. Mammography X-Ray Beam Quality Parameters

Beam code	Tube voltage (kV)	Additional filtration[a] (mm)	Half-value layer (mm Al)
Mo Anode[b]			
Mo/Mo23	23	0.032 Mo	0.288
Mo/Mo25	25	0.032 Mo	0.313
Mo/Mo28	28	0.032 Mo	0.346
Mo/Mo30	30	0.032 Mo	0.370
Mo/Mo35	35	0.032 Mo	0.404
Mo/Rh28	28	0.029 Rh	0.420
Mo/Rh32	32	0.029 Rh	0.453
Mo/Mo25x	25	0.030 Mo + 2.0 Al	0.551
Mo/Mo28x	28	0.030 Mo + 2.0 Al	0.589
Mo/Mo30x	30	0.030 Mo + 2.0 Al	0.633
Mo/Mo35x	35	0.030 Mo + 2.0 Al	0.715
Rh Anode			
Rh/Rh25	25	0.029 Rh	0.351
Rh/Rh30	30	0.029 Rh	0.438
Rh/Rh35	35	0.029 Rh	0.512
Rh/Rh40	40	0.029 Rh	0.559
Rh/Rh30x	30	0.029 Rh + 2.0 Al	0.814
Rh/Rh35x	35	0.029 Rh + 2.0 Al	0.898

[a]The additional filtration value does not include the inherent filtration, which is comprised of 1.0 mm Be from the x-ray tube window and 0.075 mm polyamid from the transmission monitor.
[b]The HVL values were measured directly using the Mo anode installed in Dec 2008.

Table 3a. ISO X-Ray Beam Quality Parameters Offered at NIST

Beam	Additional filtration (mm)[a]				First HVL[b]		Second HVL	
code	Al	Cu	Sn	Pb	mm Al	mm Cu	mm Al	mm Cu
HK10					0.042		0.045	
HK20	0.15				0.128		0.170	
HK30	0.52				0.408		0.596	
HK60	3.19					0.079		0.113
HK100	3.90	0.15				0.298		0.463
HK200		1.15				1.669		2.447
HK250		1.60				2.463		3.37
HK280		3.06				3.493		4.089
HK300		2.51				3.474		4.205
WS60		0.3				0.179		0.206
WS80		0.529				0.337		0.44
WS110		2.029				0.97		1.13
WS150			1.03			1.88		2.13
WS200			2.01			3.09		3.35
WS250			4.01			4.30		4.50
WS300			6.54			5.23		5.38
NS10	0.095				0.049		0.061	
NS15	0.49				0.153		0.167	
NS20	0.90				0.324		0.351	
NS25	2.04				0.691		0.762	
NS30	4.02				1.154		1.374	
NS40		0.21				0.082		0.094
NS60		0.6				0.241		0.271
NS80		2.0				0.59		0.62
NS100		5.0				1.14		1.19
NS120		4.99	1.04			1.76		1.84
NS150			2.50			2.41		2.57
NS200		2.04	2.98	1.003		4.09		4.20
NS250			2.01	2.97		5.34		5.40
NS300			2.99	4.99		6.17		6.30
LK10	0.30				0.061			
LK20	2.04				0.441			
LK30	3.98	0.18			1.492			
LK35		0.25			2.21			
LK55		1.19				0.260		
LK70		2.64				0.509		
LK100		0.52	2.0			1.27		
LK125		1.0	4.0			2.107		2.094
LK170		1.0	3.0	1.5		3.565		3.592
LK210		0.5	2.0	3.5		4.726		4.733
LK240		0.5	2.0	5.5		5.515		5.542

[a] The additional filtration does not include the inherent filtration. The inherent filtration is a combination of the filtration due to the monitor chamber plus 1 mm Be for beam codes LK10-LK30, NS10-NS30, HK10-HK30; for all other techniques the inherent filtration is adjusted to 4 mm Al. Details of these reference radiation qualities can be found in the following: ISO/IS 4037-1:1996(E) X and Gamma Reference Radiations for Calibrating Dosimeters and Dose Rate Meters and for Determining Their Response as a Function of Photon Energy - Part 1; Radiation Characteristics and Production Methods. [b]The x-ray tubes were installed in 2015 and 2008.

Table 3b. CCRI[a] X-Ray Beam Quality Parameters Offered at NIST

Beam code	Tube voltage (kV)	Added filtration[b] (mm Al)	(mm Cu)	Half-value layer[c] (mm Al or mm Cu)
BIPM25	25	0.373		0.24 mm Al
BIPM30	30	0.208		0.167 mm Al
BIPM40	40	3.989	0.212	2.649 mm Al
BIPM50a	50	3.989		2.291 mm Al
BIPM50b	50	1.007		1.038 mm Al
BIPM100	100	3.248		0.149 mm Cu
BIPM135	135	1.060	0.265	0.496 mm Cu
BIPM180	180	3.842	0.482	1.003 mm Cu
BIPM250	250	3.842	1.618	2.502 mm Cu

[a]BIPM, Qualités de rayonnements, Consultative Committee for Ionizing Radiation (CCEMRI) (Section I), 1972, 2, R15. Details of these reference radiation qualities can be found in: Burns, D.T. and O'Brien, M., "Comparison of the NIST and BIPM Standards for Air Kerma in Medium-Energy X-Rays," J. Res. Natl. Inst. Stand. Technol. 111, 385-391(2006) and Burns, D.T., Kessler, C. and O'Brien, M., "Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NIST, USA and the BIPM in low-energy x-rays," *Metrologia* **49** 06006 (2012).
[b]The additional filtration does not include the inherent filtration of the x-ray tubes which is approximately 3 mm Be and 1 mm Be.
[c]The HVL values were determined for the tubes installed in 2015 and 2008.

Table 4. Important dimensions and parameters for the use of the NIST standard free-air ionization chambers

Chamber	X-ray tube potential (kV)	Alignment offset[a]	Operating potential (v)	Diaphragm diameter/ID (mm)	Air absorption length (mm)
Lamperti	10 to 60	20 mm	1500	4.994/5s	39.18
Attix	10 to 50	None	2500	10.00/10u	212.7[b]
Ritz	20 to 100	15 mm	5000	10.00/10A	127.39
Wyckoff - Attix	50 to 300	None	5000	10.00/10B	308

[a] The distance down-stream from the chamber aperture to move the alignment telescope to properly align the chamber.
[b] This is variable; the value shown is used for routine use.

Table 5. Features of X-ray Systems

Features	Unipolar[a]	Bipolar[b]	Mammography[c]
Generator manufacturer	Pantak	Pantak	Gulmay
Output voltage (kV)	5 to 160	5 to 320	5 to 50
Output current (mA)	0.5 to 80	0.5 to 30	0.1 to 40
Output power (kW)	up to 4	up to 4.2	up to 1.2
kV adjustment (kV)	0.1	0.1	0.1
mA adjustment (mA)	0.01	0.01	0.1
Tube manufacturer	Thales	Comet	RTW and Lohmann
Fixed anode material	W	W	Mo and Rh[d]
Tube window (mm Be)	1	3	1
Focal spot size (mm)	5.5 x 5.5	5.5 x 5.5	3 x 3 and 5 x 5

[a] The generator was installed in December 1997 and the tube was replaced in November 2008.
[b] The generator was installed in February 1998 and the tube replaced in May 2015.
[c] The generator and the Rh tube were installed in 1994 and the Mo tube in 2008.
[d] Two x-ray tubes are used in the mammography calibration range with the same generator.

Table 6. Essential equipment to conduct calibrations in the 100 kV and 300 kV range

Description	Model	Serial number
Pantak voltage divider	ZD76390	0108-6912
Pantak voltage divider	ZD76390	0210-9603
HP high-precision digital voltmeter	3456A	2512A
HP high-precision digital voltmeter	3456A	2201A11673
Fluke high-voltage power supply	410B	2430011
Agilent	34411A	48000105
Setra barometer	350-1	340176
Wallace-Tiernan barometer	FA139	MM14869
Bertan high-voltage power supply	Series 230	9188
Bertan high-voltage power supply	Series 225	7192
Bertan high-voltage power supply	Series 225	70982
Bertan high-voltage power supply	Series 225	4183
Keithley electrometer	6517 Hi-Q	0661351
Keithley electrometer	6512	0664956
Keithley electrometer	6512	0762177
Keithley electrometer	6512	0664959
Hart thermometer Chub-E4	1529	A1B165
Hart thermometer	1504	9A183
Hopewell Designs Inc. controller		
Pantak PMC 1000 high-resolution controller	HF100	97102875CP
Pantak PMC 1000 high-resolution controller	HF 320	98013051CP
Thales	THX160/1055	581082
Comet	MXR-320/26	415574
Pantak water cooler	HF100	97102875WC
GE water cooler	OW4002	115001
Pantak generator	HF1002875-CG	9710
Pantak generator	HF320CG	0111-7137
Pantak generator	HF320AG	9801-3051

Table 7. Essential equipment to conduct calibrations in the mammography calibration range

Description	Model	Serial number
Fluke thermometer	1502A	A63236
Hart thermometer	1502	46138
Hart thermometer	1502	62495
Keithley electrometer	617 HiQ	nist564062
Keithley electrometer	617-midrange	nist564064
Keithley electrometer	617	0566314
Keithley electrometer	617	388587
Keithley electrometer	6512	0664954
Setra barometer	370	498554
Bertan high-voltage power supply	Series225	7191
Bertan high-voltage power supply	Series 225	6252
Bertan high-voltage power supply	Series 225	4183
Bertan high-voltage power supply	Series 225	4172
Velmex controller	NF90	0698662
MP1 x-ray controller	CP62	
Gulmay generator	CP62	6211
Rhodium x-ray tube	Lohmann 84005	047
Molybdenum	RTW MCD-100H-3MO	6464
Hopewell Designs, Inc. controller		nist583270
Pantak water cooler		

Table 8. Example of the optional checklist to be completed prior to requesting a calibration order

Calibration Information Request Form			
Required Dates		**Optional Dates**	
PO received		Estimated job start	
Estimated completion		Equipment arrival	
Report mailed		Inspection complete	
Equipment returned			

Contact Information
NIST Technical Contact: **Michelle O'Brien x2014**
Company:
Technical Contact:
DG Number:

Instrument Description		
Manufacturer	Model	Serial Number

Calibration Request and Cost				
SP 250 Cal ID/SKU **46011C**	Item Description **X-Ray Calibration**	Qty	Cost for this Cal ID **$**	**TOTAL**

Table 9. Beam sizes in the x-ray ranges using various beam-defining apertures and various distances

Distance from source (cm)	Beam defining aperture (cm)	Diameter at measurement point (cm)
	300 kV X-Ray Range	
	1.3	4
	1.6	5
100	1.9	7
	2.5	10
	5.1	22
	1.3	7
	1.6	10
200	1.9	14
	2.5	20
	5.1	44
	100 kV X-Ray Range	
	1.3	3
50	1.9	5
	2.5	7
	1.3	5
100	1.9	9
	2.5	13
	Mammography X-Ray Range	
100	1.3	3
	2.5	8

Table 10. Typical uncertainty analysis for tungsten x-ray air-kerma rates, relative uncertainties shown in %.

Uncertainty components	Type A	Type B
air density	0.01	0.08
charge	0.13	0.06
humidity		0.03
volume	0.04	0.01
g		0.02
W/e		0.15
air attenuation, k_a	0.05	0.02
electric field distortion, k_d		0.2
electron loss, k_e		0.1
penetration of aperture, k_l		0.04
penetration of chamber face, k_p		0.01
polarity difference	0.05	
recombination loss, k_s	0.1	
Fluorescence, k_{fl}		0.03
scattered photons, k_{sc}		0.07
quadratic sum	0.183	0.303
combined standard uncertainty	0.354	
expanded uncertainty	0.708	

Table 11. Uncertainty analysis for x-ray calibrations, shown in %

Uncertainty components	Type A	Type B
air-kerma rate	0.183	0.303
air density	0.01	0.08
charge	0.12	0.06
distance	0.01	
humidity		0.03
radiation background		
quadratic sum	0.22	0.32
combined standard uncertainty	0.388	
expanded uncertainty	0.777	

Table 12. Uncertainty analysis for air-kerma rates with the Attix chamber, shown in %

Uncertainty components	Type A	Type B
air density	0.010	0.080
charge	0.120	0.060
humidity		0.030
g		0.020
W/e		0.147
air attenuation, k_a	0.050	0.010
aperture area	0.010	0.010
plate separation	0.010	0.070
recombination loss, k_s	0.060	
scattered photons, k_p		0.200
polarity	0.1	
quadratic sum	0.175	0.279
combined standard uncertainty	0.330	
expanded uncertainty	0.660	

Table 13. Uncertainty analysis for mammography calibrations, shown in %

Uncertainty Components	Type A	Type B
air density	0.01	0.08
air kerma	0.175	0.279
charge	0.12	0.06
humidity		0.03
distance		0.02
quadratic sum	0.213	0.299
combined standard uncertainty	0.367	
expanded uncertainty	0.734	

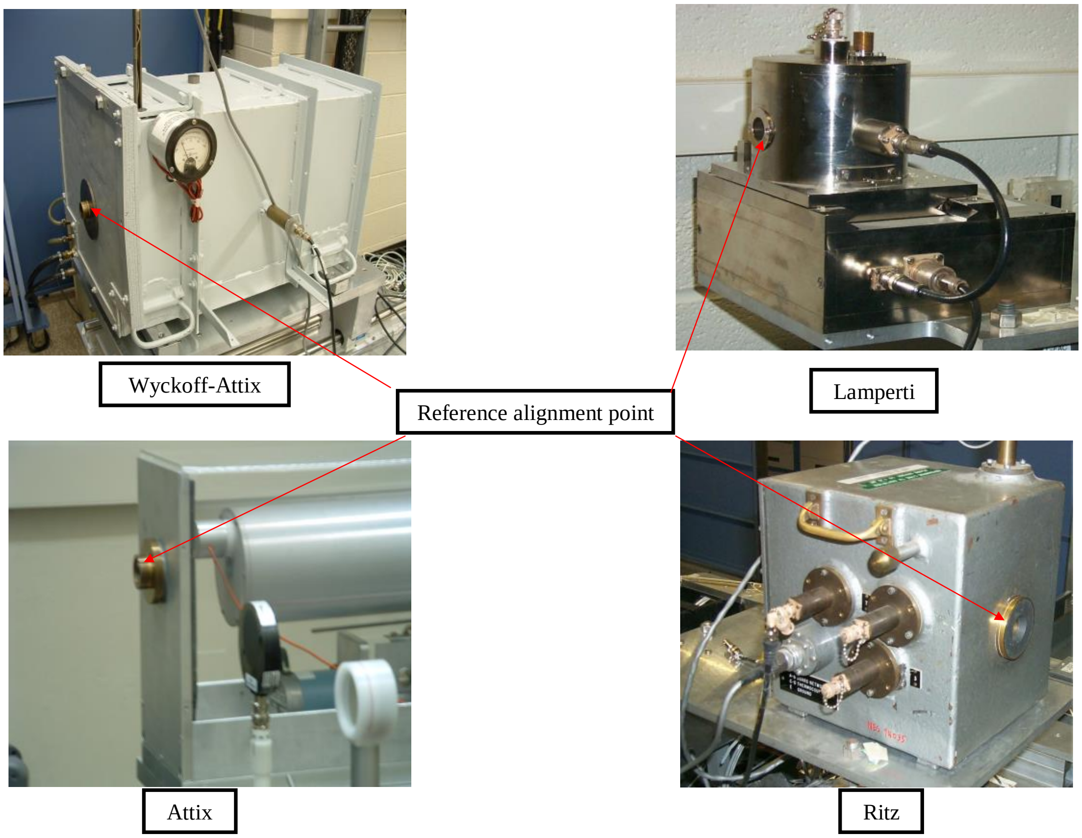


Figure 1. The four NIST x-ray standards showing the alignment points.

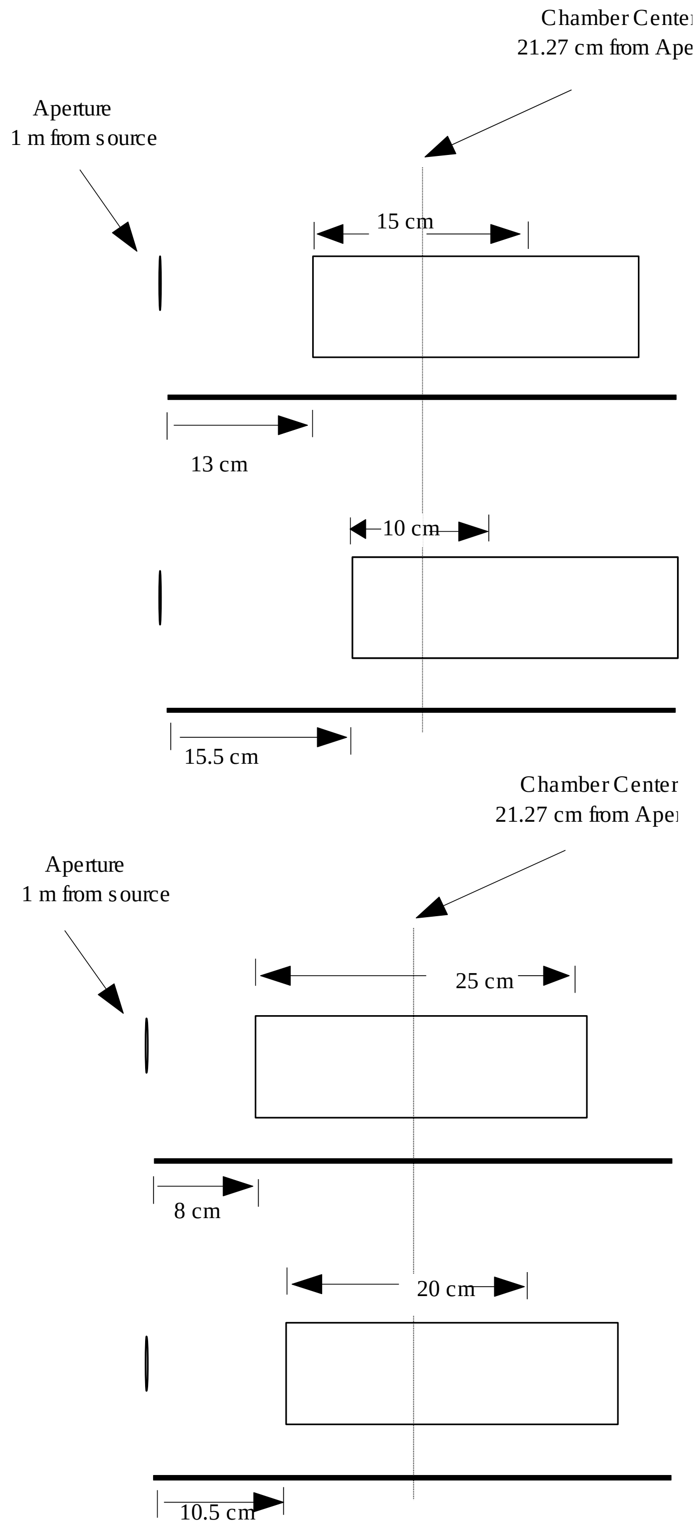


Figure 2. Typical Attix chamber configuration for air-kerma measurements.

Alignment telescope 300 kV range

Alignment telescope 100 kV range

Chamber alignment controls 300 kV range

Chamber alignment controls 100 kV range

Figure 3. Alignment controls for the calibration procedures.

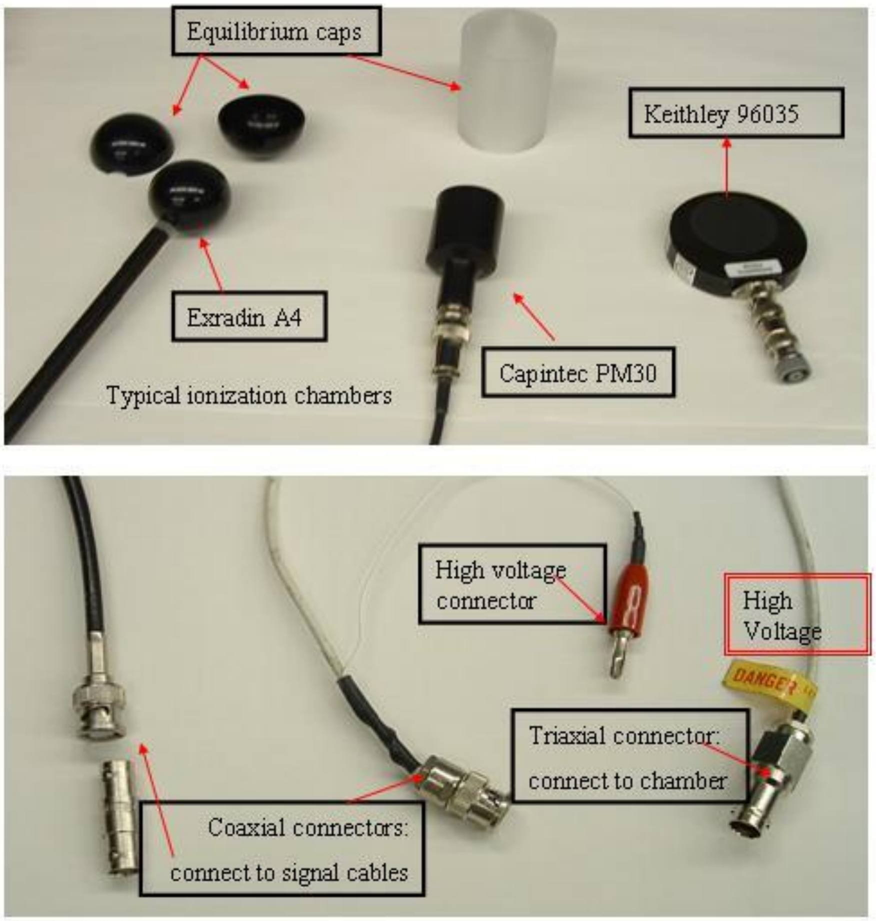


Figure 4. Typical chambers and connectors.

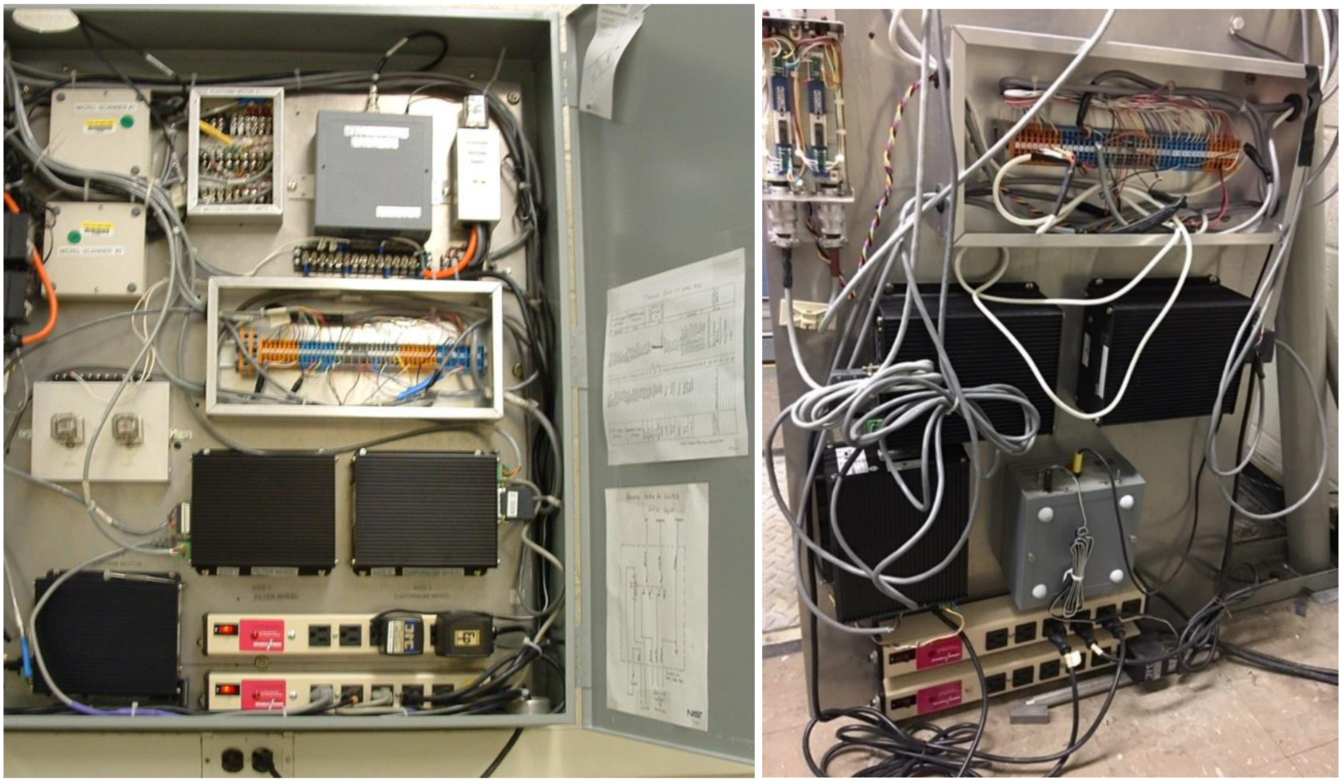


Figure 5. Motion control panels for the 100 kV and 300 kV range.

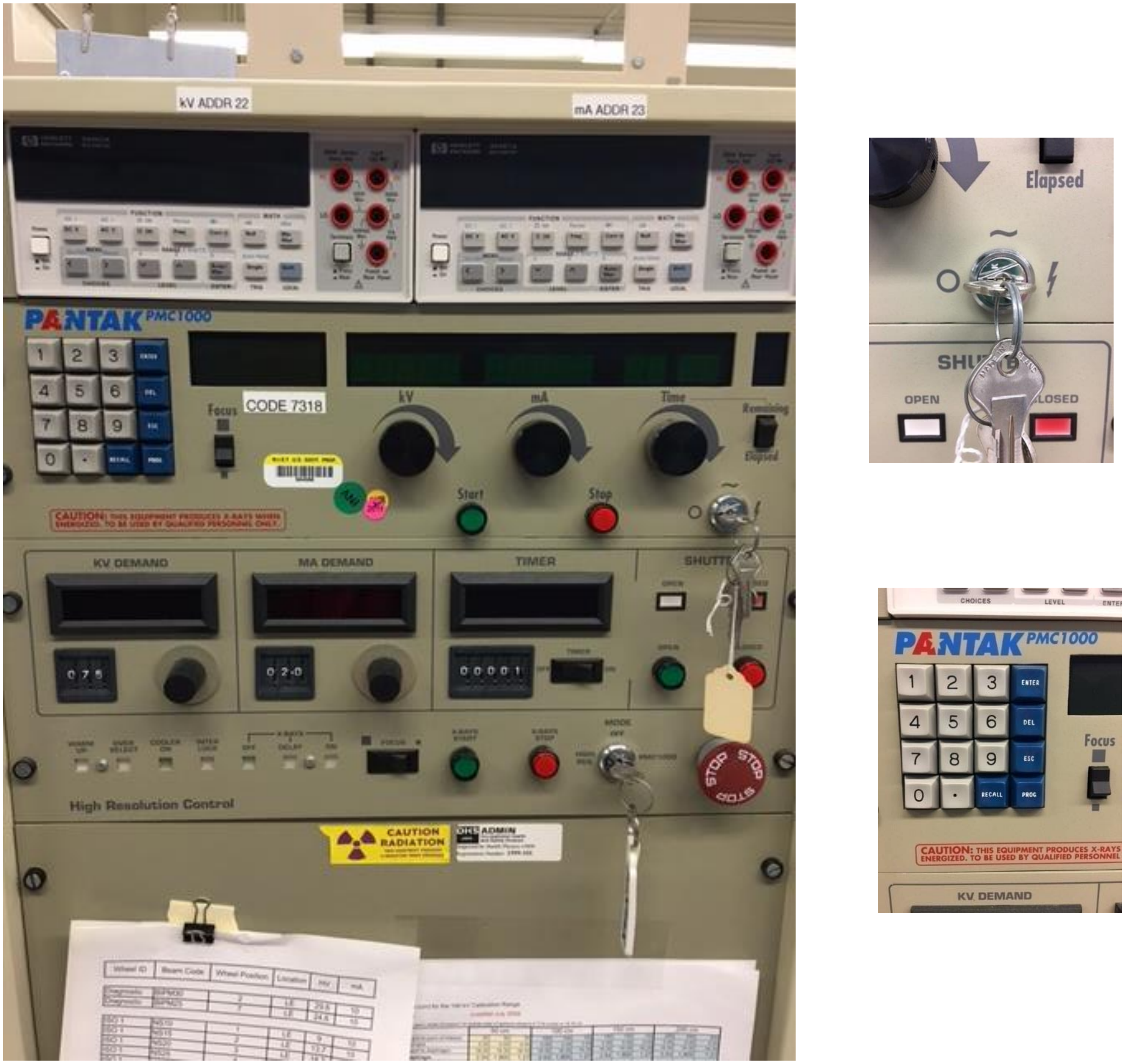


Figure 6. 100-300 kV x-ray controls.

Figure 7. 100-300kV control panel and range control.

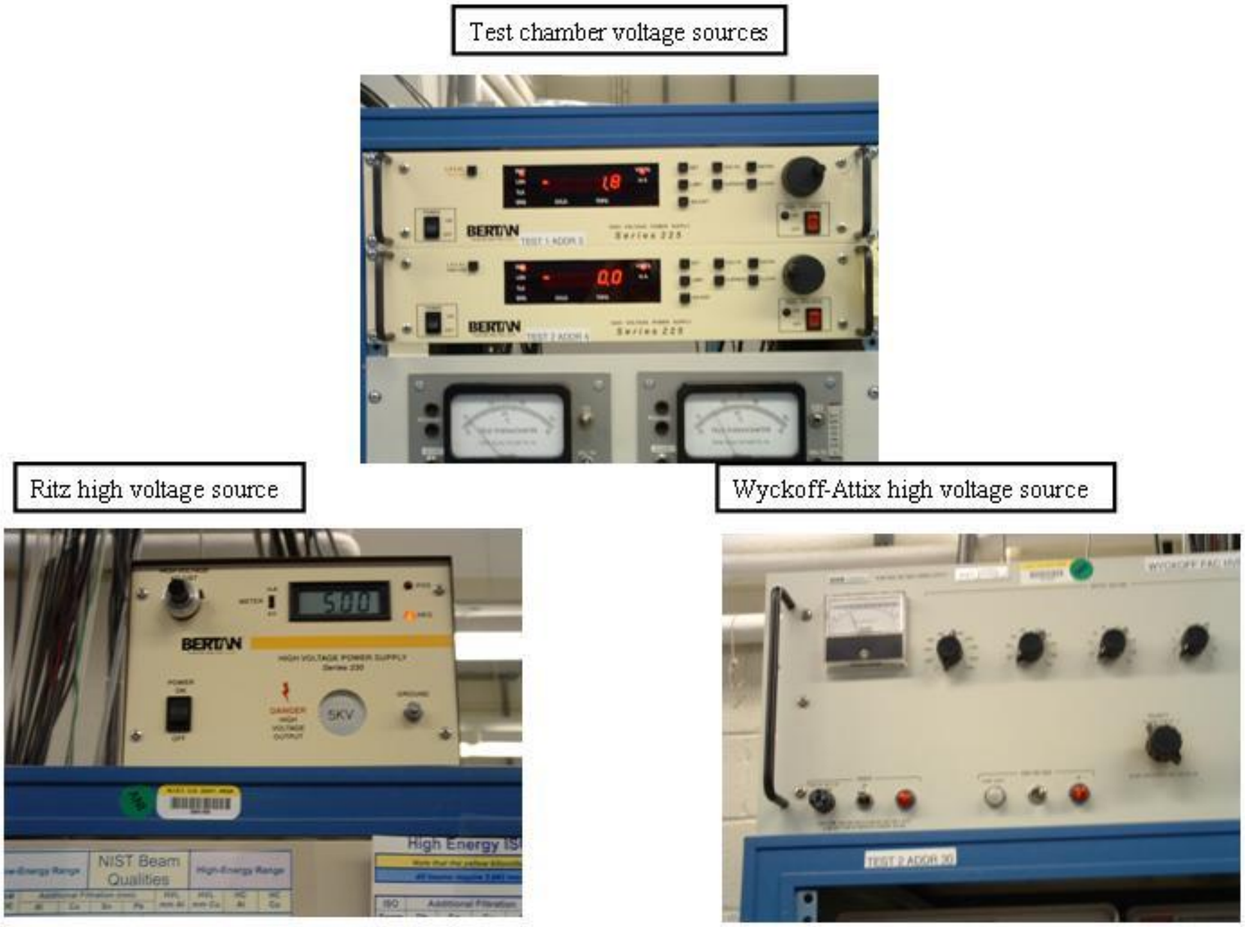
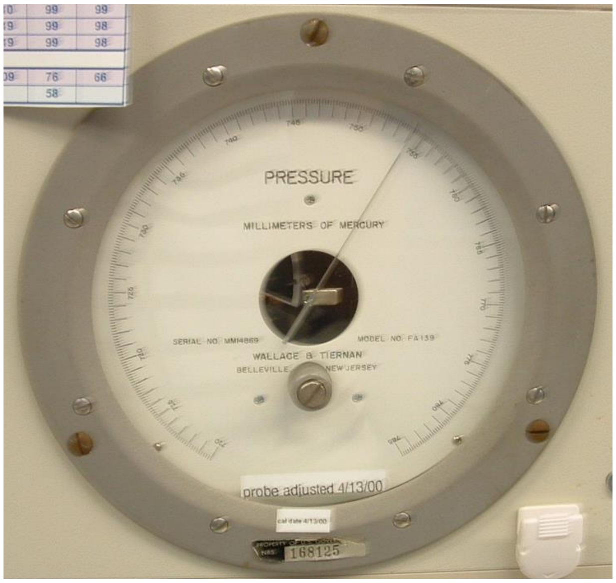
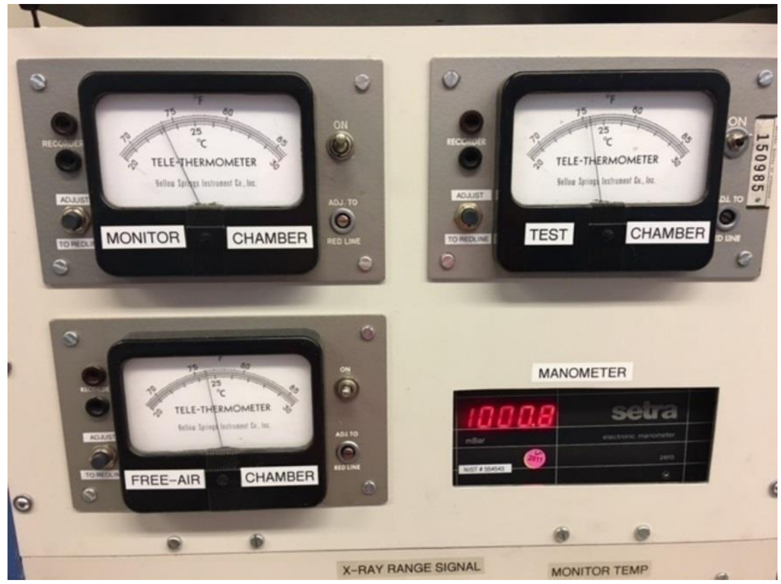


Figure 8. 100-300 kV high voltage power supplies.





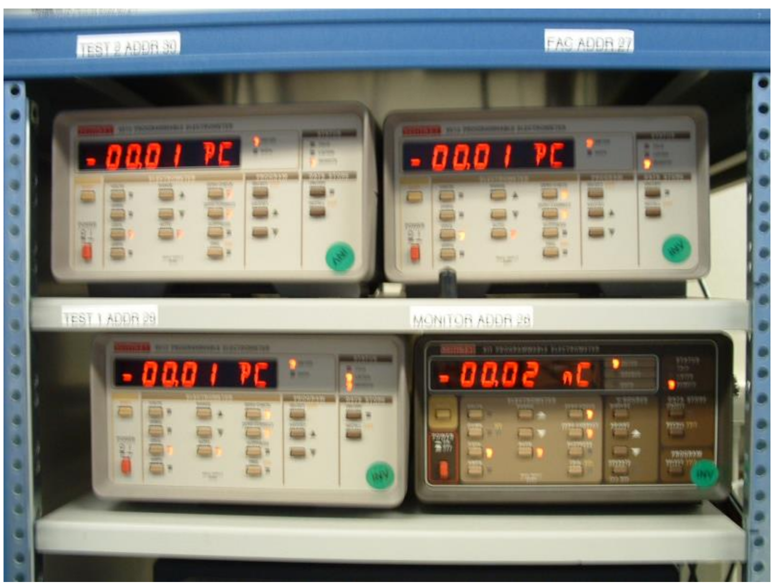


Figure 9. 100-300 kV support calibration equipment.

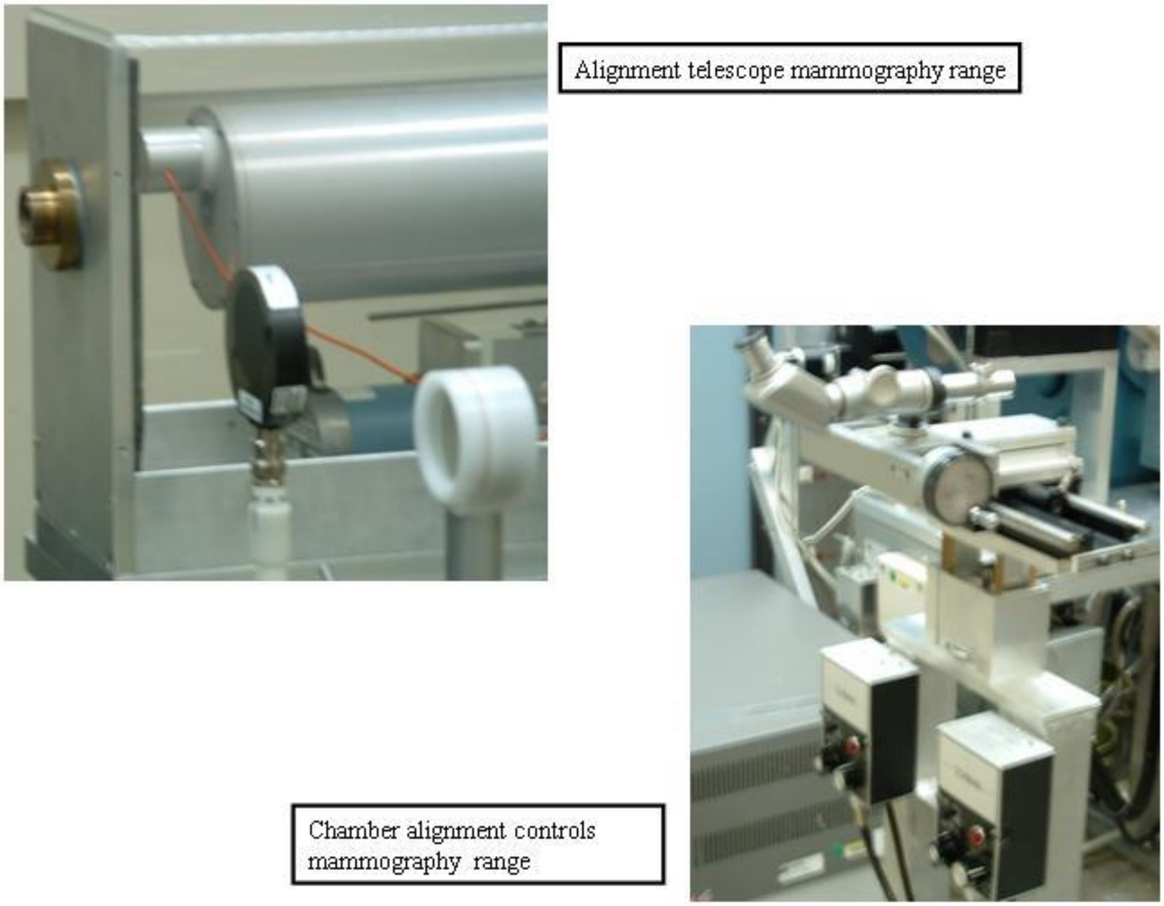


Figure 10. Mammography alignment features.

Figure 11. Mammography control panel.

Figure 12. Mammography support equipment.

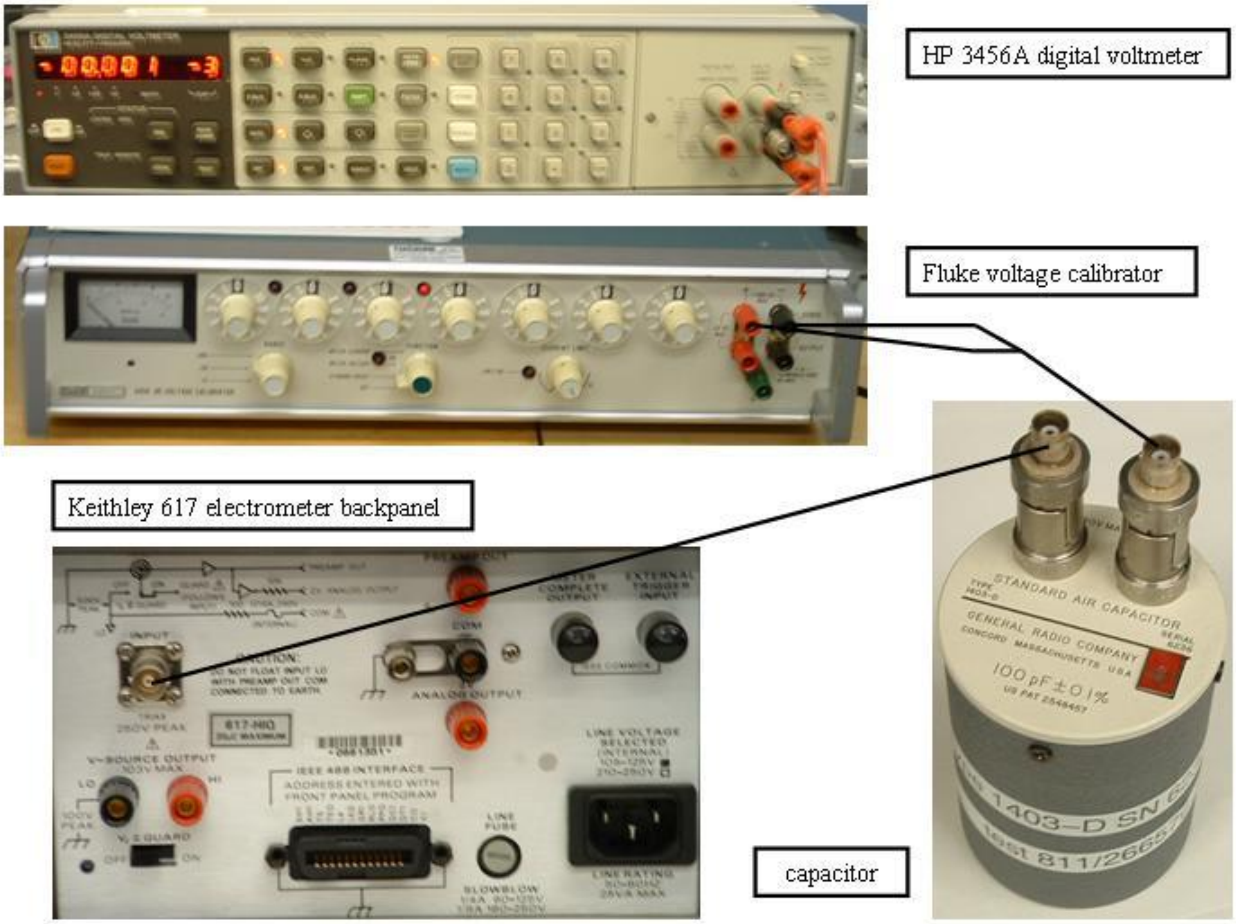


Figure 13. Electrometer calibration setup.

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Appendix 1: *Sample*

REPORT OF AIR-KERMA CALIBRATION

OF
address

Radiation Detection Chamber: chamber/model

Calibrations performed by Michelle O'Brien

Report reviewed by Ronaldo Minniti

Report approved by Michael G. Mitch, Group Leader

For the Director
National Institute of Standards and Technology
by

James M. Adams, Chief
Radiation Physics Division
Physical Measurement Laboratory

Information on technical aspects of this report may be obtained from Michelle O'Brien, National Institute of Standards and Technology, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, michelle.obrien@nist.gov, or (301) 975-2014.

Report format revised 10/17

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NIST ID 46011C ON:777
02/03/20XX
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REPORT OF AIR-KERMA CALIBRATION

OF
address

Radiation Detection Chamber: chamber/model

Chamber orientation: The cavity was positioned XXX
Chamber collection potential: A positive or negative XXX volts, with respect to the outer electrode was applied to the chamber and positive or negative charge was collected by the electrometer.
Chamber rotation: The window faced the source of radiation.
Environmental conditions: The chamber is assumed to be open to the atmosphere.
Average background current: The background current is 0.00 % of exposure current.
Temperature range:
Pressure range:
Current ratio: The current ratio at the full to half collection potential is X.XXX for an air-kerma rate of 0.0 E-0 Gy/s. A detailed study of ionization recombination was not performed. No recombination correction was applied to the calibration coefficient(s). If the chamber is used to measure an air-kerma rate significantly different from that used for the calibration, it may be necessary to correct for recombination loss.

Beam Code	Half-Value Layer (mm Al/mm Cu)	Calibration Coefficient (Gy/C) 295.15 K (22 °C) and 101.325 kpa (1 Atm)	Air- Kerma Rate (Gy/s)	Beam Diameter (cm)	Calibration Distance (cm)

NIST Calibration Conditions for X-Ray Measuring Instruments

Beam code	Additional filtration [a]				Half-value layer[b] (HVL)		Homogeneity coefficient (HC)		Effective energy (keV)
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al	Cu	
X-Ray Beam Qualities									
L10					0.037		86		
L15					0.059		70		
L20					0.070		72		
L30	0.30				0.23		60		
L40	0.53				0.52		61		
L50	0.71				0.79		63		
L80	1.45				1.81		56		
L100	1.98				2.80		58		
M20	0.27				0.15		72		
M30	0.5				0.36		65		
M40	0.89				0.74		67		
M50	1.07				1.04		68		
M60	1.81				1.68	0.052	63	60	
M80	2.86				3.08	0.1	67	61	
M100	5.25				5.10	0.2	74	55	
M120	7.12				6.77	0.31	76	53	
M150	5.25	0.25			10.30	0.66	86	63	
M200	4.35	1.12			14.73	1.64	94	68	
M250	5.25	3.2			18.49	3.2	98	85	
M300	4.25		6.5		21.77	5.3	99	97	
H10	0.105				0.051		77		
H15	0.5				0.16		87		
H20	1.01				0.36		89		
H30	4.50				1.2		86		
H40	4.53	0.26			2.93		94		
H50	4.0			0.1	4.16	0.14	92	93	38
H60	4.0	0.61			6.06	0.25	92	94	46
H100	4.0	5.2			13.51	1.15	98	92	80
H150	4.0	4.0	1.51		16.93	2.43	99	96	120
H200	4.0	0.6	4.16	0.77	19.72	4.1	99	99	166
H250	4.0	0.6	1.04	2.72	21.59	5.19	99	98	211
H300	4.1		3.0	5.0	23.55	6.19	98	98	252
S60	4.35				2.81	0.09	74	66	
S75	1.50				1.81		58		

[a]The additional filtration value does not include the inherent filtration. The inherent filtration is approximately 1.0 mm Be for beam codes L10-L100, M20-M50, H10-H40 and S75; and 3.0 mm Be for beam codes M60-M300, H50-H300 and S60.[b]The x-ray tubes were installed in 2008 and 2015.

ISO X-Ray Beam Quality Parameters Offered at NIST

Beam Code	Additional filtration[a]				First HVL[b]		Second HVL	
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al (mm)	Cu (mm)
HK10					0.042		0.045	
HK20	0.15				0.128		0.170	
HK30	0.52				0.408		0.596	
HK60	3.19					0.079		0.113
HK100	3.90	0.15				0.298		0.463
HK200		1.15				1.669		2.447
HK250		1.60				2.463		3.37
HK280		3.06				3.493		4.089
HK300		2.51				3.474		4.205
WS60		0.3				0.179		0.206
WS80		0.529				0.337		0.44
WS110		2.029				0.97		1.13
WS150			1.03			1.88		2.13
WS200			2.01			3.09		3.35
WS250			4.01			4.30		4.50
WS300			6.54			5.23		5.38
NS10	0.095				0.049		0.061	
NS15	0.49				0.153		0.167	
NS20	0.90				0.324		0.351	
NS25	2.04				0.691		0.762	
NS30	4.02				1.154		1.374	
NS40		0.21				0.082		0.094
NS60		0.6				0.241		0.271
NS80		2.0				0.59		0.62
NS100		5.0				1.14		1.19
NS120		4.99	1.04			1.76		1.84
NS150			2.50			2.41		2.57
NS200		2.04	2.98	1.003		4.09		4.20
NS250			2.01	2.97		5.34		5.40
NS300			2.99	4.99		6.17		6.30
LK10	0.30				0.061			
LK20	2.04				0.441			
LK30	3.98	0.18			1.492			
LK35		0.25			2.21			
LK55		1.19				0.260		
LK70		2.64				0.509		
LK100		0.52	2.0			1.27		
LK125		1.0	4.0			2.107		2.094
LK170		1.0	3.0	1.5		3.565		3.592
LK210		0.5	2.0	3.5		4.726		4.733
LK240		0.5	2.0	5.5		5.515		5.542

[a] The additional filtration does not include the inherent filtration. The inherent filtration is a combination of the filtration due to the monitor chamber plus 1 mm Be for beam codes LK10-LK30, NS10-NS30, HK10-HK30; for all other techniques the inherent filtration is adjusted to 4 mm Al. Details of these reference radiation qualities can be found in the following: ISO/IS 4037-1:1996(E) X and Gamma Reference Radiations for Calibrating Dosimeters and Dose Rate Meters and for Determining Their Response as a Function of Photon Energy - Part 1; Radiation Characteristics and Production Methods. [b]The x-ray tubes were installed in 2008 and 2015.

Mammography X-Ray Beam Quality Parameters

Beam code	Tube voltage (kVp)	Additional filtration[a] (mm)	Half-value layer Al (mm)
Mo Anode[b]			
Mo/Mo23	23	0.032 Mo	0.288
Mo/Mo25	25	0.032 Mo	0.313
Mo/Mo28	28	0.032 Mo	0.346
Mo/Mo30	30	0.032 Mo	0.370
Mo/Mo35	35	0.032 Mo	0.404
Mo/Rh28	28	0.029 Rh	0.420
Mo/Rh32	32	0.029 Rh	0.453
Mo/Mo25x	25	0.030 Mo + 2.0 Al	0.551
Mo/Mo28x	28	0.030 Mo + 2.0 Al	0.589
Mo/Mo30x	30	0.030 Mo + 2.0 Al	0.633
Mo/Mo35x	35	0.030 Mo + 2.0 Al	0.715
Rh Anode			
Rh/Rh25	25	0.029 Rh	0.351
Rh/Rh30	30	0.029 Rh	0.438
Rh/Rh35	35	0.029 Rh	0.512
Rh/Rh40	40	0.029 Rh	0.559
Rh/Rh30x	30	0.029 Rh + 2.0 Al	0.814
Rh/Rh35x	35	0.029 Rh + 2.0 Al	0.898

[a]The inherent filtration is approximately 1.0 mm Be from the x-ray tube window and 0.075 mm polyimide, graphite coated, from the transmission monitor. [b]The HVL values were measured directly using the Mo anode installed in Dec 2008.

CCRI[a] X-Ray Beam Quality Parameters Offered at NIST

Beam code	Tube voltage (kV)	Added filtration[b]		Half-value layer[c]
		(mm Al)	(mm Cu)	
BIPM25	25	0.373		0.240 mm Al
BIPM30	30	0.208		0.167 mm Al
BIPM40	40	3.989	0.212	2.649 mm Al
BIPM50a	50	3.989		2.291 mm Al
BIPM50b	50	1.007		1.038 mm Al
BIPM100	100	3.248		0.149 mm Cu
BIPM135	135	1.060	0.265	0.496 mm Cu
BIPM180	180	3.842	0.482	1.003 mm Cu
BIPM250	250	3.842	1.618	2.502 mm Cu

[a]BIPM, Qualités de rayonnement, Consultative Committee for Ionizing Radiation (CCEMRI) (Section I), 1972, 2, R15. Details of these reference radiation qualities can be found in the following: D. T. Burns et al, "Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the NIST, USA and the BIPM in medium-energy x-rays," Metrologia **54** 06006 (2017) and Burns, D.T., Kessler, C. and O'Brien, M., "Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NIST, USA and the BIPM in low-energy x-rays," Metrologia **49** 06006 (2012).
[b]The additional filtration does not include the inherent filtration of the x-ray tubes which is approximately 3 mm Be and 1 mm Be.
[c]The HVL values were determined for the tubes installed in 2008 and 2015.

Explanation of Terms Used in the Calibration Procedures and Tables

Air Kerma: The air–kerma rate at the calibration position is realized by a free-air ionization chamber for x radiation and is expressed in units of gray per second (Gy/s). This realization of the air kerma establishes the national standard for air kerma which can be transferred through a suitable measuring instrument, thus establishing traceability to the national standard. For a free-air ionization chamber with measuring volume V, the air-kerma rate is determined by the relation:

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1 - g_{\mathrm{air}}} \prod_i k_i$$

where

$I / (\rho_{\mathrm{air}} V)$ is the ionization current, measured by the standard, divided by the mass of air in the measuring volume

W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in dry air; the value used at NIST is $W_{air}/e = 33.97$ J/C

g_{air} is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes; the value is 0.0 (negligible) for x rays with energies less than 300 keV, and

$\Pi\, k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard.

Air kerma K, in gray (Gy), is related to exposure X, in roentgens (R), by the following equation:

$$X = \frac{K}{2.58E-4} \frac{1 - g_{\mathrm{air}}}{W_{\mathrm{air}}/e}$$

To obtain exposure in roentgens, divide air kerma in grays by 8.76E-03 for x rays with energies less than 300 keV.

Beam Code: The beam code identifies important beam parameters and describes the quality of the radiation field. NIST offers four types of reference beam qualities, as well as the ISO reference radiation qualities. NIST beam codes are referred to as L, M, H, and S beams, which stand for light, moderate, heavy, and special filtration, respectively. The number following the letter is the constant potential across the x-ray tube. The mammography beam codes are a combination of the chemical symbol of the anode and the filter respectively, followed by the constant potential, in kilovolts across the x-ray tube. The exit beam qualities, which represent the transmission of the x-rays through the breast, are created by an additional filtration of 2.0 mm of aluminum. The letter “x” ends the beam codes which refer to exit beam qualities.

Calibration Distance: The calibration distance is that between the radiation source and the detector center or the reference line. For thin-window chambers with no reference line, the window surface is the plane of reference. The beam diameter at the stated calibration distance is appropriate for the chamber dimensions.

Calibration Coefficient: The calibration coefficients given in this report are quotients of the air kerma and the charge generated by the radiation in the ionization chamber, in units of Gy/C. The average charge used to compute the calibration coefficient is based on measurements with the wall of the ionization chamber at the stated polarity and potential. With the assumption that the chamber is open to the atmosphere, the measurements are normalized to a pressure of one standard atmosphere (101.325 kPa) and a temperature of 295.15 K (22 °C). Use of the chamber at other pressures and temperatures requires normalization of the ion currents to these reference conditions using the normalizing factor *F* (see below). The calibration coefficients listed in this report can be used to calculate the air kerma through the quantification of charge collected from the test instrument in calibration conditions that approximate NIST beam codes.

Effective Energy: The effective energy is shown for those beams where it is considered a meaningful characterization of the beam quality. The effective energy for gamma radiation is the mean photon energy emitted by the radionuclide, and for x radiation it is computed from good-geometry copper attenuation data. The initial slope of the attenuation curve is used to determine the attenuation coefficient, and the photon energy associated with this coefficient is given as the "effective energy." The energy vs attenuation-coefficient data used for this purpose were taken from J. H. Hubbell, Int. J. Appl. Radiat. Isot. 33, 1269 (1982). For beam codes H50-H300, the effective energy is well represented by the equation: effective energy = $0.861V$ - 6.1 keV where V is the constant potential in kilovolts.

Half-Value Layer: The half-value layers (HVL) in aluminum and in copper have been determined by measurements with a free-air chamber for x radiation.

Homogeneity Coefficient: The homogeneity coefficient is the quotient of the first HVL and the second HVL, generally expressed as a percent.

Humidity: No correction is made for the effect of water vapor on the instrument being calibrated. It is assumed that both the calibration and the use of that instrument take place in air with a relative humidity between 10 % and 70 %, where the humidity correction is nearly constant.

Normalizing Factor *F*: The normalizing factor F is computed from the following expression: $F = (273.15 + T)/(295.15H)$ where T is the temperature in degrees celsius, and H is the pressure expressed as a fraction of a standard atmosphere. (1 standard atmosphere = 101.325 kilopascals = 1013.25 millibars = 760 millimeters of mercury)

Uncertainty: The expanded, combined uncertainty of the calibration described in this report is 0.77 %, of which 0.70 % is assigned to the uncertainty in the air-kerma rate of the NIST beam. The expanded, combined uncertainty is formed by taking two times the square root of the sum of the squares of the standard deviations of the mean for component uncertainties obtained from replicate determinations, and assumed approximations of standard deviations for all other uncertainty components; it is considered to have the approximate significance of a 95 % confidence limit. Details of the uncertainty analysis are given in: Lamperti, P.J., O'Brien, M., "Calibration of X-Ray and Gamma-Ray Measuring Instruments," NIST Special Publication 250-58 (2001).