

**RECOMMENDATIONS
ON PERFORMANCE CHARACTERISTICS
OF DIAGNOSTIC EXPOSURE METERS**



AAPM REPORT NO. 35

**RECOMMENDATIONS
ON PERFORMANCE CHARACTERISTICS
OF DIAGNOSTIC EXPOSURE METERS***

REPORT OF
TASK GROUP NO. 6
AAPM DIAGNOSTIC X-RAY IMAGING COMMITTEE

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Recommendations on performance characteristics of diagnostic exposure meters: Report of AAPM Diagnostic X-Ray Imaging Task Group No. 6

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AAPM Task Group No. 6

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Task Group 6 of the Diagnostic X-Ray Imaging Committee of the American Association of Physicists in Medicine (AAPM) was appointed to develop performance standards for diagnostic x-ray exposure meters. The recommendations as approved by the Diagnostic X-Ray Imaging Committee and the Science Council of the AAPM are delineated in this report and provide specifications on meter precision, calibration accuracy, calibration reference points, linearity, energy dependence, exposure rate dependence, leakage, amplification gain settings, directional dependence, the stem effect, constancy checks, and calibration intervals. The report summarizes recommendations for meters used in mammography, general purpose radiography including special procedures, computed tomography, and radiation safety surveys for x-ray radiography.

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I. INTRODUCTION

Because there are no short-term health effects from diagnostic exposures of x-ray radiation and because the risk of potential long-term effects has a very broad uncertainty, diagnostic exposure meters need not perform with either the accuracy or precision of meters used for therapeutic dose

measurements.^{1,2} However, the issue of just how accurate and precise diagnostic exposure measurements should be has not been formally addressed. Because of a lack of such guidelines, medical physicists have relied on their own best judgments concerning the types and frequencies of calibrations for their instruments, as well as on the overall assessments of performance characteristics. Some existing expo-

sure meters have been shown to be deficient for some diagnostic applications.^{3,4}

With advances in our knowledge about risks from exposures to low levels of ionizing radiations, the need to accurately assess absorbed doses from diagnostic x-ray examinations has increased.^{5,6} Physicists have played a key role in dose assessment for screening mammography^{7,8} and have contributed markedly to the development of low-dose examinations for all studies in children and adults.⁹⁻¹² These contributions have directly influenced technological changes to minimize radiation exposure while maximizing radiographic image quality. Good quality assurance requires that physicists monitor exposures and image quality to assure that radiation levels and radiographic quality from diagnostic examinations are within the contemporary norm. Physicists are also frequently asked to assess the dose from a diagnostic study to the conceptus of a pregnant patient. In recognition of the need to evaluate absorbed doses delivered during examinations, the Joint Commission for Accreditation of Health Care Organizations (JCAHO)¹³ requires that "...a qualified physician, qualified medical physicist, or other qualified individual...monitors doses from diagnostic radiology procedures." Regulatory agencies in some states have adopted limits on allowable exposures from diagnostic studies. Regulations may restrict, for example, the radiation levels for screening mammography. Others are more inclusive, restricting exposures for chest, kidney-ureter-bladder, lumbar spine, and other radiographs.

Exposure meters are used to evaluate the performance of imaging equipment. These evaluations assure a reliable high-quality x-ray imaging performance that helps minimize the number of repeated examinations. Meters are used to assess the linearity of output with x-ray tube current and exposure time, the output as a function of kVp and added filtration, the reproducibility of the output, the exposure per frame to the input phosphor for cine fluorography, and fluoroscopic exposure rates, among other factors.

The diagnostic physicist also uses survey-type exposure meters to assess radiation exposures to physicians and technologists from scatter and leakage radiation during in-room fluoroscopic procedures. Other uses include surveys in public areas of hospitals or in areas where mobile diagnostic studies are performed.

For each use of exposure meters a certain accuracy (i.e., the agreement between the measurement and the true exposure) and precision (i.e., the reproducibility of the measurement) are required. The use dictates the necessary performance characteristics of the meter. For example, there will be restrictions on the beam-quality dependence of exposure measurements, on ion collection efficiency as a function of exposure rate, on charge integration response or collection current response of the monitor, on the calibration of the meter, and on the precision of the meter. To address these performance requirements, the Diagnostic X-Ray Imaging Committee of the American Association of Physicists in Medicine formed Task Group 6 on Performance Standards for Diagnostic Exposure Meters. This document reviews the performance needs and, on the basis of this review, makes the recommendations discussed in Sec. IV and listed in Ta-

ble I. The rationale is discussed in Secs. II and III and summarized in Table II. The propagation of errors in exposure measurement is addressed in Sec. V.

A discussion of errors or uncertainties in measurements requires a clear definition of what they represent. Throughout this document, uncertainty limits on performance specification represent a reliability interval greater than 99% unless otherwise stated. For example, a statement that the calibration must be accurate to within $\pm 7.5\%$ means that in more than 99% of all calibrations, the calibration factors are sufficient to assure a measurement to within $\pm 7.5\%$ of the national standard. For individual measurements by an exposure meter an uncertainty of $\pm 10\%$ means that for more than 99% of all meters the meter reading is reliable to within $\pm 10\%$ of the true value. For normally distributed data, the uncertainty interval represents \pm three standard deviations (s.d.) about the mean ($> 99.7\%$ reliability), unless stated otherwise.

II. RISK ASSESSMENT

A. General radiography in adults

The potential risks from low doses of low-LET radiation are not well defined. It is assumed that a risk exists and the benefits of the diagnostic study are weighed against these potential risks, the most important of which is radiation-induced malignancy. Based on high-dose data, the excess lifetime cancer mortality from whole-body exposures is 3%-12% per sievert (Sv).^{5,6} If a risk at diagnostic doses does exist, most radiobiologists believe that a low-dose or low-dose-rate effect reduces it, and that a threshold cannot be excluded.^{5,14} Therefore, the actual uncertainty in the risk estimate for low doses ranges from a lower bound of zero to an upper bound of approximately 0.012% per mSv for a whole-body equivalent dose. Expressed another way, the excess mortality risk for a whole-body equivalent dose could be written as $0.006\% \pm 0.006\%$ per mSv. The uncertainty is $\pm 100\%$ of the absolute estimate.

Diagnostic examinations deliver doses to a limited volume of the patient's anatomy. Equivalent doses to internal organs typically range from microsieverts up to tens of millisieverts, depending on the particular examination. Because the doses are low and the uncertainty in the absolute risk is high for radiation-induced cancer, an exposure measurement accurate to within $\pm 30\%$ would be sufficient to assess the absolute risk.

More frequently, exposure measurements in diagnostic radiology are used to estimate relative risks associated with various radiographic procedures, techniques, or technologies. For example, it is worthwhile to know that one technology produces half the absorbed dose of another.' In this case, the potential radiation-induced excess risk to individuals receiving examinations with the lower dose technology is halved. However, if the uncertainty in the dose estimate is $\pm 30\%$ as suggested in the previous paragraph, propagation of this uncertainty causes the factor of 2 reduction in excess risk to have an uncertainty ranging from about 1.1 to 2.9. Such an uncertainty interval due to measurement errors is too broad for meaningful comparisons. (This approxima-

tion is the Taylor series approximation for the ratio of two uncorrelated variables. It is not possible to state the exact uncertainty interval because many of the sources of measurement uncertainty are systematic while others are not. How errors combine depends on whether or not the same exposure meter is used for both measurements as well as other factors. This range of 1.1 to 2.9 occurs if two different meters are used.)

If each of the two equivalent dose measurements of the previous example have an uncertainty of only $\pm 10\%$, then the uncertainty in the reduced excess risk is between about 1.7 and 2.3, which permits the conclusion that a substantive reduction is achieved. An uncertainty in measurement of $\pm 10\%$ is sufficient for such comparisons. For some investigations, e.g., research, narrower limits of uncertainty may be required. The uncertainty interval can be markedly reduced in these cases by employing the same exposure meter in all measurements, thereby eliminating some systematic errors due to calibration and energy dependence.

B. Risk assessment in children

On the basis of a relative risk model, most epidemiological evidence suggests that children are more susceptible to radiation-induced cancer than adults.^{5,6} On the other hand, because of their smaller size, exposures in diagnostic examinations of children are generally far less than those for adults." Exposure measurements to within an uncertainty of $\pm 10\%$ should be sufficient to assess the potential risks of pediatric examinations.

C. Screening mammography

With the advent of screening mammography, the need to compare the potential risks of radiation-induced breast cancer with the potential benefits of diagnosing early spontaneous breast cancer became more acute. In screening mammography, large numbers of women without clinical signs of breast cancer are exposed to the ionizing radiation. Of these only a fraction actually benefit from early cancer detection. In order to minimize the risk of radiation-induced breast cancer, the mammographic examination must deliver the lowest absorbed dose consistent with diagnostic accuracy.

Determination of glandular tissue dose for an individual patient is inaccurate due to variations in compression and in estimates of the glandular tissue content of the breasts of different patients. Estimates are typically made for doses to a standardized breast that is composed of 50% fat and 50% glandular tissue and is about 4.5 cm thick under firm compression. Average glandular doses are calculated from free-in-air entrance exposures, using conversion factors provided in the scientific literature.^{8,16-18} These dose estimates depend on beam quality and entrance exposure, both of which have uncertainty. The conversion factors themselves have uncertainty and the exposure across the breast can vary by up to 50% from the chest wall to the nipple because of the heel effect. These factors should be considered when assessing the required precision and accuracy for exposure meters used to measure the entrance exposures.

For reasons previously mentioned, comparative dose esti-

mates between various mammographic units for a standard breast are more important than the absolute dose estimate since the purpose of the measurement is to assure that doses are at an acceptable state-of-the-art level for screening. In order to provide meaningful comparisons between units, an uncertainty of $\pm 10\%$ in exposure measurement is sufficient.

D. Risk assessment during pregnancy

Physicists are frequently asked to assess dose to a conceptus from diagnostic procedures. Some evaluations are prospective, others retrospective. Retrospective analyses entail more potential for inaccuracy because they frequently involve recollection on the part of physicians or technologists about fluoroscopic on-time and the number of discarded films and repeated radiographs. Furthermore, technique factors such as fluoroscopic kVp and mA have to be recalled and are sometimes unknown.

The judgment as to what uncertainty is acceptable for the exposure meter measurement depends on the consequences of such uncertainty on patient care. The contribution should not greatly increase the upper limit dose estimate. What constitutes too great an increase is a matter of judgment. Consider the present state of knowledge about low-dose radiation effects on the unborn. The types and quantifications of risks are highly uncertain. Measurement of dose to within an uncertainty of $\pm 10\%$ should be sufficient. A $\pm 10\%$ error in measurement is much less than the error introduced by the other uncertainties in the estimation of absorbed dose if the evaluation is done retrospectively. If the evaluation is performed prospectively wherein many of the sources of uncertainty can be eliminated (i.e., fluoroscopy on-time, kVp, mA, and conceptus position can be documented), a $\pm 10\%$ uncertainty represents a realistically modest margin of measurement error when compared to uncertainties in potential risk.

E. Computed tomography

Computed tomography (CT) is a relatively high-dose examination by diagnostic standards. Typically, organs examined during CT receive about 30 to 60 mGy. The dose is relatively uniform throughout the imaging volume, varying by a factor of approximately 40% from the surface to the central-axis for multislice abdominal examinations."

Conventional ionization chambers are designed for total active volume irradiation. For this reason, use of such chambers for dose estimates in CT is at best difficult because of the problem of partial volume irradiation." It is more appropriate and common to employ a pencil-type ionization chamber to infer a multislice computed tomographic dose from a measurement on a single slice. This dose is related to the computed tomographic dose index (CTDI).²⁰ The purposes of this measurement are to assess the absolute dose for a particular technique, to compare doses for different techniques, and to compare doses among scanners. In order to make adequate comparisons, an uncertainty in measurement of $\pm 10\%$ is sufficient.

F. Exposures to personnel and the public

Surveys of radiation levels in public areas or in radiographic rooms are performed to determine the potential risks to individuals. Since the absolute risks have a broad range of uncertainties, the accuracy of exposure measurements need only be sufficient to compare the potential risks of one environment with respect to an accepted standard. Such surveys must take into account workloads, use factors, and occupancy factors which all have their own uncertainties. Survey exposure measurements to within an accuracy of $\pm 30\%$ should be more than sufficient to assess the adequacy of protection because of the other uncertainties as well as the low exposures and the very low potential risks associated with such regulated environments.

III. ACCEPTANCE TESTING AND QUALITY ASSURANCE

A. Linearity

For consistent imaging performance with manual techniques, linearity of output with tube current (mA) should not deviate by more than $\pm 10\%$ across the range of mA stations." Federal regulations* are less stringent and require that the "... average ratios of exposure to the indicated milliamperes-seconds product (mR/mAs) obtained at any two consecutive tube current settings shall not differ by more than 0.10 times their sum." This effectively means that no two consecutive mA stations may result in measurements of mR/mAs that differ by more than 20%.

It is important that the measured linearity be a characteristic of the output of the equipment and not be affected by any exposure rate dependence, nonlinearity, or imprecision of the exposure meter. If all measurement uncertainties of the meter were random and normally distributed, then one could reduce the standard error for any one mA station by increasing the number of measurements. In order to limit the number of exposures required for the test and to ensure that the imprecision of the meter not contribute markedly to the error in linearity measurement, it is recommended that the precision of the meter be within $\pm 3\%$ ($\pm 1\%$ standard deviation).

Exposure-rate dependence and nonlinear electric circuit response of the exposure meter are systematic errors and cannot be minimized by multiple measurements. Therefore, they must be small on an absolute scale when compared to the performance criteria of the x-ray unit. For this reason, it is recommended that the error due to rate dependence not exceed 1% across the range of exposure rates utilized in the test and the error due to nonlinearity in exposure meter circuit response be within the greater of $\pm 0.5\%$ or $0.013 \mu\text{C kg}^{-1}$ (0.05 mR) across the range of exposures for which the instrument is designed. Maximum exposure rates for quality control tests are about $8 \text{ mCkg}^{-1}\text{s}^{-1}$ (30 Rs^{-1}).

B. Reproducibility

A reasonable standard of performance for modern technology requires that the x-ray output at a given kVp and mAs should not vary by more than $\pm 10\%$ (a standard deviation of about $\pm 3\%$). The federal requirements²² for per-

formance of x-ray equipment are less stringent and state that "For any specific combination of selected technique factors, the estimated coefficient of variation of radiation exposures shall be no greater than 0.05." This means that the standard deviation must be less than $\pm 5\%$ of the mean. The requirement states that this be determined from ten consecutive measurements made within 1 h.

The precision of the exposure measuring device must be much better than the acceptable precision of the machine output to ensure that the measured precision of the x-ray machine is not adversely influenced by the measuring device. This requires that the precision of diagnostic exposure meters not exceed $\pm 3\%$ ($\pm 1\%$ standard deviation). (Assuming normally distributed variations, combining in quadrature a $\pm 3\%$ variation from the meter with a $\pm 10\%$ variation in output results in a net observed variation of about $\pm 10.4\%$.)

C. Output as a function of beam quality

For quality assurance, acceptance testing, and regulatory needs, diagnostic exposure meters must measure output at a variety of beam energies. The required accuracy for any one measurement at any given kVp and half-value layer (HVL) is governed by the purpose for which the measurement is made. In general the energy dependence of the exposure meter should not add to the error in the absolute exposure measurement to an extent that would make the total error exceed $\pm 10\%$.

D. Half-value layer measurements

To reduce entrance skin exposure, filtration is added to x-ray systems. Federal regulations²² require minimum levels of filtration and many users employ much more. The adequacy of filtration is checked by measuring the HVL in millimeters of aluminum, usually 1100 type. The required accuracy of HVL measurements places restrictions on the reproducibility and energy dependence of the exposure meter.

In mammography, a change in HVL of 0.01- to 0.015-mm aluminum is about equivalent to a 1-kV change in beam quality. For quality control in mammography, changes in HVL of 0.02 mm should be measurable. Such accuracies in measurement of HVL are possible but can be compromised by factors other than the exposure meter.⁴ Instabilities in radiation output or kVp of the x-ray equipment introduce errors into such measurements. Impurities in 1100 aluminum can vary causing differences in HVL measurement. This is especially so for mammography⁴ where variations in HVL of $\pm 4\%$ are possible due solely to variations in impurity levels.

The sources of error in the measurement of half-value layer can be large depending on the equipment and the methods used to acquire the data. The performance of the exposure meter should be such that under the best of conditions, the errors introduced in the measurement of HVL are small compared to all other errors. The principal sources of uncertainty introduced by performance of the exposure meter result from its energy dependence, imprecision, nonlinearity,

and exposure rate dependence.³ Lack of precision is seldom a significant problem for such measurements and can be reduced by multiple measurements. The error due to nonlinearity and exposure rate is likewise seldom a problem for this measurement since the exposures only range over a factor of about 2 and rates can be kept quite low. The error due to energy dependence at energies above 50 kVp is usually small. The use of exposure meters to measure HVL in general radiography is not a driving factor in setting performance standards for general purpose exposure meters. However, it has been shown that severe energy dependence in the mammographic range will result in significant errors in mammographic HVL measurements.⁴ The change in correction factor over the range of mammographic beam qualities (from about 20 to 50 kVp) should be less than 5% for mammographic exposure meters in order to assure an adequately small error in the measurement of HVL.

E. Radiography and fluoroscopy

Exposure rates for automatic brightness controlled fluoroscopy are federally regulated²² not to exceed "10 roentgens per minute at the point where the center of the useful beam enters the patient." Under special high-exposure-rate conditions other restrictions apply. Although exposure rates are specified at a point, the shape, volume, and area of the ionization exposure meter prohibit measurement at a point and introduce inherent error. X-ray fields in diagnostic radiology are nonuniform and variations of many percent over the field area can be anticipated. Because of this variation, the position of the chamber in the beam can influence the exposure rate. This error is exacerbated by the size of the sensitive portion of the detector and the spatial variation of the sensitivity over the area of the detector.

Since the requirement specifies 10 R/min (0.043 mC kg⁻¹s⁻¹) as a maximum limit, it would be necessary for a user to ensure that his/her measurement plus the uncertainty in the measurement not exceed this maximum. If the uncertainty in the measurement is $\pm 10\%$ then the user would have to set the maximum output at 9.0 R/min by his/her meter. This would ensure a maximum rate of not more than 9.9 R/min which is within the limit. A $\pm 10\%$ uncertainty would also ensure that exposure rates measured on the same machine by several individuals (physicists, service personnel, and regulatory inspectors) agree to within a reasonable norm. However, such a practice could also result in an actual exposure rate of only 8.1 R/min if the error in the measured rate is 10% on the high side. This is too low for some applications. To avoid this possibility, either the accuracy of the measurement will have to be much better than $\pm 10\%$ or regulatory agencies will have to accept maximum rates of 10 R/min $\pm 10\%$. For reasons discussed later accuracies better than $\pm 10\%$ are not guaranteed due to calibration and other errors.

Spot radiographic exposures during fluoroscopy are a special consideration. Because of the under-table configuration, source-to-skin distance is usually about 450 mm. For barium enema studies with a tube voltage of 110 kVp and a tube current of 400 mA, high exposure rates result. Exposure rates with backscatter in place are typically 3-8 mCkg⁻¹

s⁻¹ (10-30Rs⁻¹) with rates of more than 20 mCkg⁻¹s⁻¹ (80 Rs⁻¹) possible for some situations. Barium enema spot radiography produces the highest exposure rates encountered in diagnostic radiology. Exposure meters should not have an exposure rate dependence that introduces a total error in the measurement beyond $\pm 10\%$.

IV. RECOMMENDATIONS ON PERFORMANCE CHARACTERISTICS

In consideration of the foregoing uses of diagnostic exposure meters, it is recommended that the combined uncertainty due to bias and random errors of in-beam exposure measurements not exceed $\pm 10\%$ of the true value, i.e., in more than 99% of all measurements the measured value will be within $\pm 10\%$ of the true value. It is therefore required that the combined uncertainties as a result of precision, calibration, nonlinearity, exposure rate, energy dependence, and all other factors not exceed $\pm 10\%$. For survey meters used in diagnostic radiology it is recommended that the accuracy of measurements be such that, for more than 99% of the measurements, the measured value will be within $\pm 30\%$ of the true value. In order to meet these and other previously discussed recommendations, the guidelines outlined in Table I are recommended for performance of exposure meters used in diagnostic radiology.

A. Precision

1. Mammographic, general purpose, and CT meters

Given 20 identical exposures to the ionization chamber, the mammographic, general purpose, or CT diagnostic exposure meter shall perform such that the standard deviation in the readout is less than 1% of the mean when the exposure to the meter is at least 0.08 mCkg⁻¹ (300 mR) for any exposure time from 0.01 s up to 10 s.

2. Integrating radiographic survey meters

The standard deviation in the readout for 20 identical exposures to the survey meter shall not exceed 3% of the mean value when the exposure to the meter is at least 0.03 mC kg⁻¹ (100 mR) for any exposure time from 1 s up to 10 s.

B. Accuracy

At least three factors contribute to the inaccuracy of an exposure measurement. These are: calibration error, energy dependence, and exposure-rate dependence.

1. Calibration

a. Mammographic, general purpose, and CT meters. It is recommended that the calibration of a mammographic, general purpose, or CT diagnostic exposure meter at a specific calibration kilovoltage and HVL be such that after application of calibration correction factors, any measurement made by that meter under identical conditions and at standard temperature and pressure agree to within $\pm 7.5\%$ of the standard maintained by the National Institute of Standards and Technology (NIST). The geometric orientation of the ionization chamber with respect to the beam at the

TABLE I. Recommendations for performance characteristics, and testing of diagnostic exposure meters.

Item	Application(s)	Recommendation
Precision	Mammography (less than 50 kVp) General radiography (greater than 60 kVp), and CT Radiographic survey meters ^d	< 1% standard deviation < 3% standard deviation
Calibration accuracy	Mammography, general purpose, and CT Survey	To within $\pm 7.5\%$ of NIST standard ^d To within $\pm 20\%$ of NIST standard. ^b
Calibration reference points	Mammography	3 points: ~0.25 mm Al (> 99.9% pure) HVL ~0.35 mm Al (> 99.9% pure) HVL ~1.0 mm Al (> 99.9% pure) HVL
	General	3 points: ~1.5 mm Al (1100 alloy) HVL ~3.5 mm Al (1100 alloy) HVL ~5.0 mm Al (1100 alloy) HVL
	CT	2 points: ~3.5 mm Al (1100 alloy) HVL ~10.0 mm Al (1100 alloy) HVL
	Survey	2 points: ~0.35 mm Al (> 99.9% pure) HVL ~10.0 mm Al (1100 alloy) HVL
Linearity		<0.5% or <0.013 μCkg^{-1} (0.05 mR) deviation from linearity for any exposure within readout range when exposure rate is unchanged.
Energy dependence	Mammography	< 5% change in correction factor from 0.25 mm Al (> 99.9% pure) HVL to 1.0 mm Al (> 99.9% pure) HVL
	General	< 5% change in correction factor from 1.5 mm Al (1100 alloy) HVL to ~ 10.0 mm Al (1100 alloy) HVL
	CT	< 5% change in correction factor from 3.5 mm Al (1100 alloy) HVL to 10.0 mm Al (1100 alloy) HVL
	Survey	< 30% change in correction factor from 30 kVp 0.35 mm Al (> 99.9% pure) HVL to 10.0 mm Al (1100 alloy) HVL
Exposure rate dependence	Mammography	< 1% change from calibrated response for any exposure rate < 0.5 $\text{mCkg}^{-1}\text{s}^{-1}$ (2 Rs^{-1})
	General	< 1% change from calibrated response for any exposure rate up to 8 $\text{mCkg}^{-1}\text{s}^{-1}$ (30 Rs^{-1}) and < 3% change in response for exposure rate up to 20 $\text{mCkg}^{-1}\text{s}^{-1}$ (80 Rs^{-1})
	CT	< 1% change from calibrated response for any exposure rate < 1.5 $\text{mCkg}^{-1}\text{s}^{-1}$ (6 Rs^{-1})
	Survey	< 5% change from calibrated response for exposure rates up to 0.3 $\text{mCkg}^{-1}\text{min}^{-1}$ (1 Rmin^{-1})
Leakage	All	Less than 0.1 μCkg^{-1} (0.4 mR) in 30 s from 0.0 mCkg^{-1} and less than 0.5% in 30 s from 2.6 mCkg^{-1} (10 R) or max reading, whichever is less. Must be correctable to within 0.1%.
Amplification gain setting (other than temperature and pressure, see Table III)	All	Less than 0.5% change from calibrated reading after all gains are fully changed and reset.
Directional dependence	All	User determined
Stem effect	All	Less than 0.5%
Exposure rate meter	Mammography, general and CT Survey	Less than 0.5% difference in rate mode versus integrated mode. Less than 2% difference in rate mode versus integrated mode.
Exposure rate dependence, constancy checks and precision checks. ^e	All	Before and after initial calibration and annually thereafter (or following repair)

TABLE I. (Continued.)

Item	Application(s)	Recommendation
Calibration intervals	All	Initial calibration to include all points. Biennial calibrations at a single point closest to normal use. If constancy check shows significant deviation, repair, if necessary, and recalibrate at all points.

^aDiagnostic x-ray survey-type or large chamber volume meters. These specifications do not apply to survey instruments used in nuclear medicine.

^bThe + / - interval represents the > 99% certainty interval.

^cRecalibrate or repair if check suggests that recommended performance standards are not met.

point of calibration will be specified. Uncertainty due to the geometric size and shape of the meter must be included in the estimate of calibration error. This accuracy is judged by the task group to be the best compromise between the capabilities of the calibration laboratories and the needs of the users.

b. Integrating survey meters. Calibration of survey meters used in diagnostic radiology shall be such that, after application of calibration correction factors, any measurement made by that meter at a specific calibration kilovoltage and HVL and at standard temperature and pressure agrees to within $\pm 20\%$ of that made by the standard maintained by the NIST. To meet this requirement, it is sufficient that users calibrate such survey meters by comparing performance against a general purpose or mammographic meter that has been calibrated against a secondary standard.

2. Energy dependence

To keep the uncertainty in exposure measurement to within the ranges specified in Secs. II and III, it is necessary to ensure that interpolation of a correction factor for a given beam quality will not introduce more than a 1% error for diagnostic meters and not more than a 5% error for survey meters. The following recommendations are therefore made.

a. Mammographic meters. The correction factors for mammographic exposure meters at beam qualities of 0.25 mm HVL (~ 20 kV) in aluminum (> 99.9% pure), 0.35 mm HVL (~ 30 kV), and 1.0 mm HVL (~ 50 kV) shall not differ from each other by more than 5% (Ref. 23) when all gains and settings of the exposure meter remain unchanged for each beam quality calibration.

b. Generalpurpose meters. The correction factor for general purpose exposure meters at beam qualities of 1.5 mm HVL of 1100 aluminum (~ 60 kVp), 3.5 mm HVL (~ 90 kVp), and 10.0 mm HVL shall not differ from each other by more than 5% (Ref. 23) when all gains and settings of the exposure meter remain unchanged for each beam quality calibration.

c. CT meters. The correction factor for CT exposure meters at a beam quality of 3.5 mm HVL (~ 90 kVp) shall not differ from that of 10.0 mm HVL by more than 5% (Ref. 23) when all gains and settings of the exposure meter remain unchanged for each beam quality calibration.

d. Integrating survey meters. The correction factor for sur-

vey exposure meters at a beam quality of 0.35 mm HVL (~ 30 kVp) in aluminum (> 99.9% pure) shall not differ from that at 10.0 mm HVL by more than 30% when all gains and settings of the exposure meter remain unchanged for each beam quality calibration.

3. Linearity

The average reading of the meter in response to different exposure levels shall be within $\pm 0.5\%$ of the anticipated linear value or within $0.013 \mu\text{C kg}^{-1}$ (0.05 mR), whichever is greater, for any exposure within the range of the readout scale when the exposure rate for each reading remains unchanged.

4. Exposure-rate dependence

The specifications, applying to ion collection efficiency and to the electronic conversion of the collected charge to a displayed readout, are given in Table I and are self-explanatory. They are designed to meet the performance requirements previously discussed. Methods for users to test exposure-rate dependence have been previously reported.^{24,26}

C. Other factors affecting precision and accuracy

The following factors or features can contribute to inaccuracies and imprecision in measurements and should be checked by users.

1. Leakage current

With the meter initially set at $0.0 \mu\text{Ckg}^{-1}$ the meter reading should not change by more than $\pm 0.1 \mu\text{Ckg}^{-1}$ (0.4 mR) over a 30-s period. In addition, after the meter is exposed to 2.6 mCkg^{-1} (10 R) or its maximum value, whichever is less, the reading should not change by more than $\pm 0.5\%$ within 30 s. During the test the meter must remain in the operating mode with no manipulation of the meter either electrically or mechanically. If the leakage exceeds these values, the leakage must be sufficiently stable that the bias in the meter reading is correctable by calculation to within 0.1% for exposures in excess of 10 mR and to within 0.05 mR for exposures less than 10 mR.

TABLE II. Summary of uses of ionization exposure meters and measurement uncertainties.

Use	Uncertainty not associated with meter	Recommended maximum limits on measured uncertainty
Absolute risk assessment	The uncertainty in risk coefficients from epidemiological and animal research for low level exposures is very large ($\pm 100\%$)	$\pm 30\%$ total
Comparative risk assessment	Regardless of the magnitude of the risk, comparing risks for similar doses has only a small uncertainty due to differences in beam quality, exposure rate, etc.	$\pm 10\%$ total
Conceptual dose evaluation surveys	Very large uncertainties in absolute risks ($\pm 100\%$) Same uncertainty as for absolute risk assessment	$\pm 10\%$ total $\pm 30\%$ total
Linearity of output	Quality control criteria permit a variation of $\pm 10\%$ in linearity of machine output from the anticipated linear value.	$\pm 3\%$ in precision; $< 1\%$ in exposure rate dependence; $< 0.5\%$ or $< 0.013 \mu\text{Ckg}^{-1}$ (0.05 mR) deviation from linear response, whichever is greater.
Reproducibility of x-ray output	Quality control criteria permit a $\pm 10\%$ variation in machine output for a given technique	$\pm 3\%$ in precision
Output versus beam quality Half-value-layer	Errors can be large, see Ref. 4	Energy dependence must be low enough to ensure less than $\pm 10\%$ total error. Energy dependence must keep total HVL measurement error to within about ± 0.02 mm of Al for mammography and $\pm 2\%$ for general radiography
Fluoroscopy entrance exposure rates High exposure rate radiography	Uncertainties are associated with nonuniformities in radiation field.	$\pm 10\%$ total $< 1\%$ deviation in response for exposure rates up to $8 \text{ mCkg}^{-1} \text{ s}^{-1}$ (30 Rs^{-1}) and $< 3\%$ deviation in response for rates up to $20 \text{ mCkg}^{-1} \text{ s}^{-1}$ (80 Rs^{-1})

2. Amplification gain

Many instruments are provided with amplification gains on the readout in order to correct for various factors. These factors include temperature and pressure correction and calibration factors. Changing and resetting of these gains may introduce errors in accuracy and precision. Precision of the instrument at all useful gain settings must meet the requirements in Sec. IV A. Temperature and pressure corrections must remain accurate to within 1.5% as specified in Table III. The accuracy of the reading at all other gain settings must not change from the accuracy of the calibration by more than 0.5% when all gains are fully changed and reset to the operational settings.

3. Directional dependence

Ionization chambers of exposure meters are calibrated with unidirectional beams. The response to x-rays originating from other directions may differ. This can introduce error into a measurement as, for example, with scattered radiation conditions. Users should determine the error introduced in a measurement because of such dependence of their ionization chamber.

4. Stem effect

The unavoidable irradiation of exposure meter components such as coaxial leads and electronic circuitry in the handle or "stem" of the ionization chamber should not result in a reading that causes the response to differ by more than 0.5% if such components were not exposed.

5. Exposure rate measurement

Many exposure meters provide a means by which the exposure rate can be directly determined. Exposure meters are typically calibrated in the integrated exposure mode, not in the exposure rate mode. The response of the meter in the exposure rate mode should agree to within 0.5% of the integrated calibration for general purpose meters and to within 2% for survey meters. An invasive technique employing a constant current source can be used to validate the response in the rate mode. Use of radioactive sources to calibrate survey meters in the rate mode may not be appropriate because of the disparity in energies of such sources and the energies commonly encountered in diagnostic radiologic surveys. In principal, compliance with this specification could also be tested in a carefully designed study that compares readings

TABLE III. Summary of recommended performance characteristics for exposure meters.

Source of uncertainty	Type of uncertainty	Maximum recommended uncertainty			
		Mammographic	General purpose	CT	Survey meters
Calibration	Systematic bias	$\pm 7.5\%$	$\pm 7.5\%$	$\pm 7.5\%$	$\pm 20\%$
Calibration factor interpolation (energy dependence)	Systematic bias	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	$\pm 5\%$
Temperature and pressure correction ^c	Systematic bias	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 1.5\%$
Gain settings	Systematic bias	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$
Precision ^b	Random	$\pm 3\% / \sqrt{n}$	$\pm 3\% / \sqrt{n}$	$\pm 3\% / \sqrt{n}$	$\pm 9\% / \sqrt{n}$
Exposure rate	Systematic bias	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	$\pm 5\%$
			$(\leq 8 \text{ mCkg}^{-1}\text{s}^{-1})$		
			$\pm 3\%$		
			$(\leq 20 \text{ mCkg}^{-1}\text{s}^{-1})$		
Linearity	Systematic bias	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$
Stem effect	Systematic bias	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$
Leakage ^c	Systematic bias	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 0.1\%$
Rate mode	Systematic bias		$\pm 0.5\%$...	$\pm 2\%$

^aMaximum uncertainty is that due to either meter-internal corrections or corrections applied by user.

^b n is the number of exposure measurements.

^cUncertainty specified is that after calculational correction for leakage.

from the exposure rate mode to readings in integrated exposure mode. However, this procedure has not been well tested and the experimental errors may prove to be large. Research into noninvasive techniques for the user to verify the calibration of the exposure rate mode is lacking at this time.

6. Computed tomography pencil ionization chambers

In order to produce an accurate response, the sensitivity of the pencil chamber along its volume should be uniform. The positional sensitivity of the chamber should be checked by the user at acceptance and after any repair. Any nonuniformities in response should be incorporated into the error analysis of the measurement.

D. Constancy checks

All meters should be intercompared with at least one other meter before and after calibration and then annually for constancy of response at two or more beam qualities. Exposure rate dependence, precision, leakage, and other factors previously discussed, should be checked before and after calibration and yearly thereafter or after major repair of the electronic readout circuitry. If changes are noted that render the meter outside performance specification limits, the suspect meter should be repaired if necessary or recalibrated, whichever is the appropriate action.

E. Calibration intervals

Following initial calibration at all beam qualities specified in Table I, a biennial calibration at a single beam quality representative of normal use is recommended. Recalibration at all beam qualities is unnecessary unless the chamber is repaired, a new probe is purchased, or a change in response

from that at initial calibration is suspected as indicated during annual constancy checks.

V. ERROR PROPAGATION IN EXPOSURE MEASUREMENT

The previous section recommends that diagnostic radiographic exposure measurements be accurate to within $\pm 10\%$. For survey work the accuracy should be $\pm 30\%$. In Table III errors characteristic of exposure meters, their type, and their maximum magnitude as recommended in this report are summarized. The only random error in exposure measurement is that due to the imprecision of the meter. Therefore, it is the only error that can be reduced by multiple measurements. All other uncertainties are systematic; that is, they bias the measurement. Only the uncertainty due to exposure-rate dependence is reasonably predictable according to sign. Ion collection losses at high exposure rates are most likely to render the reading too low, resulting in an error with a positive value. (It is conceivable that in some meter designs the error could produce too high a reading and, therefore, the negative sign should be kept in performance specification.)

To meet the $\pm 10\%$ accuracy guideline for diagnostic measurements and the $\pm 30\%$ guideline for surveys the combination of all sources of uncertainty must not exceed these limits. To ascertain how these errors might combine, it is useful to separate uncertainties into four categories: (1) calibration associated biased uncertainties, (2) data acquisition biased uncertainties, (3) random measurement uncertainties, and (4) meter intrinsic biased uncertainties.

A. Calibration associated biased uncertainties

In the measurement of exposure at a given beam quality, the calibration factor introduces a biased uncertainty be-

cause the same factor is used for every measurement. However, among all meters calibrated by all laboratories it is probably reasonable to assume that the differences between the specified calibration factors and the true calibration factors are randomly distributed. It is also reasonable to assume that the error introduced in the correction factor at a particular beam quality as a result of interpolation between calibration factors for different beam qualities is also randomly distributed. To estimate the combined uncertainty due to the calibration factor error and the interpolation error the specified uncertainty limits of Table III are added in quadrature. This yields net calibration uncertainties of $\pm 7.57\%$ for diagnostic meters and $\pm 20.1\%$ for survey meters. These limits mean that more than 99% of all calibrated meters have calibration factors that under identical exposure rate conditions will result in measurements that agree with the national standard to within these limits (i.e., within $\pm 7.57\%$ for diagnostic meters and $\pm 20.1\%$ for survey meters).

B. Data acquisition biased uncertainties

Uncertainties associated with temperature and pressure corrections and in establishing gain settings introduce a bias in exposure measurement for each measuring session because these factors are not changed during the session. The magnitude of the error is random from session to session and these error limits may be added in quadrature to establish the uncertainty limits due to these factors. The combined uncertainty for meters matching the performance specifications is 1.58%.

C. Random measurement uncertainties

Random errors due to imprecise ion collection and electrical noise in the meter should not result in a standard deviation in measurements in excess $\pm 1\%$ ($\pm 3\sigma = \pm 3\%$) for diagnostic meters and $\pm 3\%$ ($\pm 3\sigma = \pm 9\%$) for survey meters. The standard error in a measurement due to meter imprecision can be reduced by acquiring multiple measurements.

D. Meter intrinsic biased uncertainties

Uncertainty in a measurement of exposure will be biased because of specific characteristics of the meter. Such uncertainties include those due to exposure rate dependence, non-linearity, stem effect, leakage, and exposure rate mode of operation. How these uncertainties combine depends on the conditions of the measurements. For example, the stem effect error will depend on field size and beam energy. Some errors may be correlated. For example, linearity might be worse at higher exposure rates. Furthermore, the errors among meters are not randomly distributed. For example, the exposure rate dependence will predominantly bias a reading to a low value and the bias will be greater at higher rates. To assess whether the performance specifications are adequate it is necessary to discuss a few separate circumstances.

1. Integrated exposure measurements at low exposure rates

The uncertainties due to calibration, temperature and pressure, gain settings, and meter precision can be added in quadrature to assess the dispersion of readings from many meters and many sessions. This uncertainty is $\pm 8.3\%$. For diagnostic measurements of integrated exposure at low exposure rates the specified maximum meter intrinsic errors for exposure rate dependence ($\pm 1.0\%$), linearity ($\pm 0.5\%$), stem effect ($\pm 0.5\%$), and leakage ($\pm 0.1\%$) are not likely to combine in such a way as to increase the error past $\pm 10\%$. Therefore, at low exposure rates the specifications should be sufficient to ensure that more than 99% of all readings from all diagnostic meters are within $\pm 10\%$ of the national standard. A similar assessment demonstrates that the survey meter specifications are also sufficient.

2. Exposure rate measurements

Exposure rate measurements in diagnostic radiology are always done at low exposure rates, e.g., fluoroscopy rates and survey exposure rates. In such measurements the precision specification is not applicable. The uncertainty for diagnostic meters due to calibration, temperature and pressure, and gain settings is about 7.73%. The additional uncertainty introduced by exposure rate dependence (1%), linearity (0.5%), leakage (0.1%), stem effect (0.5%), and the change to the exposure rate mode (0.5%) is sufficiently small to ensure that more than 99% of all readings from all diagnostic meters are within $\pm 10\%$ of the national standard. A similar assessment demonstrates that the survey meter specifications are also sufficient.

3. Integrated exposures at high exposure rates

The uncertainties due to calibration, temperature and pressure, gain settings, and meter precision, as in Sec. V D 1 are estimated at 8.3%. For diagnostic measurements of integrated exposures at high exposure rates, the meter intrinsic errors of $\pm 3\%$ for exposure rate dependence, $\pm 0.5\%$ each for linearity and stem effect and 0.1% for leakage may or may not be sufficient to ensure measurements accurate to within $\pm 10\%$ of the national standard in more than 99% of such measurements by all meters. Whether this is so depends on many factors that cannot be assessed in this report. Very few measurements of diagnostic exposures are done at more than $8 \text{ mCkg}^{-1}\text{s}^{-1}$. Presumably the accuracy of the meter would become gradually less as the rate increases rendering the greatest discrepancy at $20 \text{ mCkg}^{-1}\text{s}^{-1}$. These situations would be rare and the likelihood of all uncertainties combining to an error greater than 10% from the national standard is sufficiently small as to make the performance specifications at high exposure rates acceptable.

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¹The theoretical relationships between exposure, absorbed dose, and equivalent dose are well known. The absorbed dose and equivalent dose from diagnostic examinations are frequently derived on the basis of exposure measurements. In this article, the word "exposure" is used when a measurement by an exposure meter is indicated. The terms "dose" and "equivalent dose" are used when referring to risk assessments or biological effects.

²At diagnostic energies the quantity air kerma is directly proportional to exposure, that is K (mGy) = 8.73 x X (R), where K is air kerma in mGy and X is exposure in roentgens. Alternatively, K (mGy) = 33.8 x X (mCkg⁻¹), where X is exposure in millicoulombs per kilogram of air. Quotation of air kerma may be more practical than quotation of exposure and exposure recommendations in this report can be converted to air kerma by use of the above equations.

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