Designation: F3094 − 14

Standard Test Method for Determining Protection Provided by X-ray Shielding Garments Used in Medical X-ray Fluoroscopy from Sources of Scattered X-Rays[1]

This standard is issued under the fixed designation F3094; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method establishes a procedure for measuring the relative reduction in the intensity of X-radiation provided by shielding garments to the human user under conditions simulating actual use.

1.2 This test method provides a condition simulating X-rays generated between 60 and 130 kV that are scattered through an angle of 90° by a water equivalent material.

1.3 This test method applies to both leaded and no-leaded radiation protective materials.

1.4 This test method provides a method for inclusion of secondary radiations generated within the protective material into a more realistic evaluation of radiation protection.

1.5 The values given in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Some specific hazards statements are given in Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

F1494 Terminology Relating to Protective Clothing

F2547 Test Method for Determining the Attenuation Properties in a Primary X-ray Beam of Materials Used to Protect Against Radiation Generated During the Use of X-ray Equipment

2.2 *IEC Standard:*[3]

IEC 61331-1 Ed. 2.0 Protective Devices Against Diagnostic Medical X-radiation: Part 1 – Determination of Attenuation Properties of Materials

3. Terminology

3.1 *Definitions:*

3.1.1 *attenuation, n*—for radiological protective material, the fractional reduction in the intensity of the X-ray beam resulting from the interactions between the X-ray beam and the protective material when the X-ray beam passes through the protective material.

3.1.1.1 *Discussion*—It is important to note that the measurement of attenuation (as specified by Test Method F2547) specifically excludes the contribution of secondary radiation from the measurement. The present standard provides a method for incorporating those contributions of radiation dose to the wearer of protective garments. (See 3.1.10.)

3.1.2 *coefficient of variation*—the ratio of the standard deviation of a sample to the sample mean.

3.1.3 *exposure, n*—for radiological purposes the amount of ionization charge of one sign produced in a defined volume of dry air at standard temperature and pressure, caused by interaction with X-rays. Exposure is expressed in units of coulombs/kg of air in SI units. An older unit called the Roentgen (R) is also used, where 1 R = 2.58×10^{-4} C/kg.

3.1.4 *fluorescent radiation, n*—a form of secondary radiation following photoelectric collisions between X-rays and orbital electrons of heavier elements such as those used in protective materials, whereupon electron rearrangements at the atomic level result in the emission of one or more fluorescent photons.

3.1.4.1 *Discussion*—Measurements to include fluorescent radiation are important because they may contribute to the radiation exposure to the wearer of radiation protective garments.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Electrotechnical Commission (IEC), 3, rue de Varembé, P.O. Box 131, CH-1211 Geneva 20, Switzerland, http://www.iec.ch.

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3.1.5 *half-value layer (HV), n*—the thickness of 99.9 % pure aluminum in millimetres (commonly designated mm Al) that reduces the intensity of an X-ray beam by one half of its initial value.

3.1.5.1 *Discussion*—HVL is commonly used to designate the penetrating ability of an X-ray beam containing many X-ray energies (as is the case with standard X-ray sources). A higher value of Al in mm Al would indicate a more penetrating X-ray beam. Note that HVL may also be specified in materials other than Al, although only Al is used in this document.

3.1.6 *ionization chamber*—a device that measures the electrical charge liberated during the ionization of air molecules by electromagnetic radiation (X-rays for the purposes of this test method), expressed in units of coulombs per kg of air.

3.1.6.1 *Discussion*—The measurement of exposure is defined for an air ionization chamber. The chamber used in this method must be of a flat, parallel-plate design.

3.1.7 *kilovolts, or kilovolts peak (kV or kVp), n*—for the purposes of radiological protection, the maximum electrical potential across an X-ray tube during exposure.

3.1.7.1 *Discussion*—The kV or kVp determines the maximum photon energy in kilo-electron volts (keV) of an X-ray beam; standard X-ray beams contain many photon energies most of which are less than this maximum value.

3.1.8 *lead equivalency*—for radiological protective material the thickness in millimetres (commonly designated mm Pb) of greater than 99.9 % purity that provides the same attenuation as a given protective material.

3.1.8.1 *Discussion*—Radiation protective materials are commonly made with little or no lead thus lead equivalence will vary with X-ray energy and with the composition of the protective material. Lead equivalence should be specified at a specific energy. This test method specifies a method for determining the attenuation in pure lead materials but does not require a specific lead equivalence. If lead equivalence is specified, it should be specified at a single scatter equivalent condition.

3.1.9 *primary X-rays, n*—the X-rays emitted from the target of an X-ray tube subjected to an accelerating potential sufficient to cause X-ray emission.

3.1.9.1 *Discussion*—Primary X-rays are distinguished from secondary X-rays emitted from a material exposed to primary X-rays. Secondary X-rays are generally less penetrating than primary X-rays.

3.1.10 *protection rating, n*—for the purposes of radiological protection in this test method, the percentage of exposure at the skin surface of the wearer of the protective garment relative to the exposure on that surface in the absence of the protective garment, measured under scatter equivalent conditions for a particular radiation quality.

3.1.11 *scatter equivalent conditions*—specific primary X-ray spectra defined in terms of kV and HVL that simulate radiation scattered from a water equivalent medium measured at 90° to the beam incidence on that medium.[4]

3.1.11.1 *Discussion*—Measuring the actual degree of protection from scattered X-rays provided by radiation protective garments under real world conditions is technically difficult and subject to large uncertainties. Actual scatter intensities are too low and measurements have excessively high uncertainties when evaluated in practical conditions. The scatter equivalent conditions describe conditions that conservatively approximate the energies of 90° scatter produced when a water medium (body of a human or animal) is exposed to Test Method F2547 beam qualities. Use of the surrogate primary beams provides conditions that are practical to test under field conditions.

3.1.12 *scatter radiation, n*—a form of secondary radiation where X-radiation is deflected to a changed direction with or without a loss in energy by collisions between X-ray photons and orbital electrons of atoms in the path of the X-rays; scattering events in medical procedures mainly occur with loss of energy due to the Compton Effect such that the average energies of scattered X-rays are less than that of the direct primary beam.

3.1.13 *secondary radiation, n*—radiation that is produced in a material by scattering or emission when the material is exposed to a source of X-rays.

3.1.13.1 *Discussion*—Secondary radiation is of importance because: (*1*) the hazard to medical X-ray fluoroscopy workers is principally from X-rays scattered from the patient and other materials within the primary X-ray beam, (*2*) fluorescent radiation produced within the protective material can contribute to the radiation exposure to the wearer of the radiation protective garments.

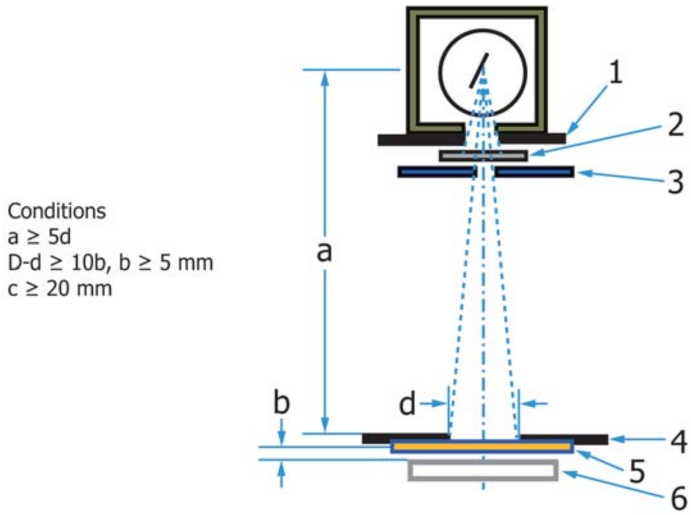
3.1.14 *standard sample dimensions*—test samples and lead standards cut to an area suited to the measurement setup in Fig. 1, ideally by using a template.

3.1.14.1 *Discussion*—It may be desired to test finished protective clothing that are not cut to standard sample dimensions using this test method. This may be done, but may require a special test jig to support the material in proper orientation and configuration to meet this test method. Such a procedure is not described in this test method.

3.1.15 *wave form ripple, n*—for radiological purposes the peak to peak variation in the voltage potential applied to the X-ray tube during exposure. Greater voltage ripple (common in older X-ray generators) tends to reduce the intensity and penetrating ability of the resulting X-ray beam compared to units with little or no voltage ripple.

3.2 Some definitions are reproduced for convenience from Test Method F2547. For definitions of other terms related to protective clothing used in this test method, refer to Terminology F1494.

[4] McCaffrey, J. P., Tessier, F., and Shen, H., "Radiation Shielding Materials and Radiation Scatter Effects for Interventional Radiology (IR) Physicians," *Med. Phys.*, Vol 39 (7), July 2012.



1. Diaphragm
2. Beam filtration
3. Diaphragm
4. Measuring diaphragm
5. Test material
6. Flat air ionization measuring chamber

1. IEC 61331-1 Ed. 2.0 Protective Devices Against Diagnostic Medical X-radiation, Part 1: Determination of Attenuation Properties

2. McCaffrey, J.P., Tessier, F., and Shen, H., "Radiation Shielding Materials and Radiation Scatter Effects for Interventional Radiology (IR) Physicians, *Med. Phys.*, Vol 39 (7), 2012, pp. 4537–4546.

FIG. 1 Test Setup

4. Summary of Test Method

4.1 A primary X-ray beam with a standardized X-ray spectrum and a constant intensity with the conditions listed in Table 1 for the scatter equivalent conditions employed to measure the attenuation in test samples using the inverse broad-beam conditions in Fig. 1.

4.2 Attenuation can be measured for scatter equivalent energies corresponding to all primary beam energies as defined by Test Method F2547; however, it is recommended that three measurements be used in standard reports. These measurements correspond to most common fluoroscopic conditions at 80 kV, a high kV condition for a standard fluoroscope at 100 kV, and a condition corresponding to scatter produced from CT scanning at 130 kV. These scatter equivalent conditions correspond to direct beam measurement at 70, 85, and 105 kV with filtrations adjusted to achieve HVL's of 3.4, 4.0, and 5.1 mm Al respectively.

TABLE 1 Standard X-ray Qualities (Columns 1 and 2) and Scatter Equivalent Qualities[4]

Direct Beam		90° Scatter Equivalent	
kV	HVL (mm Al)	kV	HVL (mm Al)
60	2.9	50	2.6
70	3.3	60	2.9
80	4.0	70	3.4
90	4.3	75	3.7
100	5.2	85	4.0
110	5.5	90	4.3
120	6.3	100	4.5
130	6.7	105	5.1

5. Significance and Use

5.1 This test method is designed to provide a standardized procedure to ensure comparable results between manufacturers, testing laboratories, and users.

5.2 This test method attempts to realistically quantify the radiation protection provided by radiation protective garments under real world conditions for workers primarily exposed to scattered radiation in medical fluoroscopy work.

5.3 This test method is designed to simulate exposure conditions to radiation scattered from the body of the patient undergoing fluoroscopy through an angle of 90° from the primary X-ray beam.

5.4 The test method is designed to include contributions of radiation dose to the wearer from secondary radiation emitted from the shielding material.

6. Apparatus

6.1 *Primary X-ray Beam Source*—A variable power X-ray generator coupled to a tungsten anode X-ray tube with the following characteristics:

6.1.1 Wave form ripple cannot exceed 3 %, and may not employ capacitor discharge methods where the voltage potential falls more than 5 % during the test exposure.

6.2 *kV Monitoring*—Kilovoltage shall be actively measured during testing with an invasive or non-invasive kV measuring device capable of measuring potential within 0.5 kV of the actual tube.

6.2.1 The coefficient of variation in voltage potential cannot exceed 0.05 in four consecutive exposures using the potential setting(s) for testing.

6.3 *Exposure Measurement:*

6.4 An ionization chamber and electrometer capable of measuring from 0.258 to 1290 µC/kg (1 mR to 5 R) and calibrated for use with X-rays generated under conditions specified by Test Method F2547.

6.5 The coefficient of variation in exposure cannot exceed 0.05 in four consecutive exposures when measured through 0.5 mm of Pb.

6.6 *Noise*—Detector signal measured under the same conditions (integration time) of the measurement but without X-rays shall not be more than 1 % of the minimum measurement recorded through any test material.

6.7 *Test Setup*—The apparatus may use either a vertically or horizontally directed X-ray beam provided that the geometry conforms to that described in Fig. 1.

6.7.1 Beam defining apertures.

6.7.1.1 Beam apertures designated 1 and 3 in Fig. 1 are normally incorporated into most medical X-ray system collimator assemblies. If such an apparatus is used they need not be added. Aluminum filtration needed to adjust the HVL to test conditions may be added through a slot provided on some collimators or may be positioned on the output surface of the collimator.

6.7.1.2 The collimator should be adjusted so that all dimensions of the field at aperture 4 exceed the dimensions of that aperture on all sides by at least 1 cm.

6.7.1.3 Aperture 4 should be constructed of lead with a thickness of at least 2 mm with external dimensions at least 2.5 cm larger than the largest dimensions of the ionization chamber on all chamber margins.

6.7.2 *Geometry:*

6.7.2.1 Aperture 4 should be positioned so that its distance to the X-ray tube focus (*a* in Fig. 1) is at least five times the diameter of the opening (*d*).

6.7.2.2 The spacing between test material and the ionization chamber (*b*) shall not exceed 5 mm during measurements.

6.7.2.3 Spacing between the X-ray detector and any other surface along the direction of the X-ray beam shall be 700 mm or more.

7. Hazards

7.1 Workers performing this test should be qualified to operate an X-ray machine and should be familiar with standard methods of radiation safety.

8. Sampling and Test Specimens

8.1 Samples should be prepared to simulate the total thickness of protective shielding material that is normally in place in the finished garment. Components of the garment that provide support but no shielding function may be excluded during testing; however, this condition should be clearly specified in the report.

8.1.1 The surface area of the sample must be such that neither length nor width is less than 1 cm greater than the outer dimension of the air ionization chamber (D) in Fig. 1.

8.1.2 If samples are prepared from materials and not intact garments, specify a specific sample width and length appropriate for the measurement setup.

8.1.3 Care must be taken in sample positioning so that the sample is completely flat and completely obstructs the opening in aperture 4 in all tests.

8.2 Protective garments constructed with regions having more than one shielding value shall require measurement of test specimen representative of each of the shielded regions.

9. Preparation of Apparatus

9.1 Measure and document the kVp accuracy for each kV setting used in the measurement.

9.1.1 If a non-invasive kV measurement device is used it may be positioned at the edge of the X-ray field on the surface of aperture 4. Make sure that the field completely covers its sensitive area. If this device is used, document kV at every exposure.

9.2 Measure and document the exposure reproducibility using settings employed in measurement of the sample with the greatest attenuation or with lead foil standard of equivalent attenuation.

9.3 Measure and document detector noise using integration times of at least 10 s.

9.4 Measure and document the HVL for each kV setting used in measurements.

9.5 Measure and document the transmission through the lead foil standards at each kV using standard #1 alone, #2 alone, #3 alone, #1 + #3 together, #2 + #3 together, and #1 + #2 + #3 together.

9.6 Measure and document the kV accuracy again at the end of the measurement session.

10. Calibration and Standardization

10.1 The kVp meter and the ionization chamber shall be calibrated not less than annually to National Institute of Standards and Technology (NIST) traceable standards.

10.2 Lead standards shall be prepared as follows:

10.2.1 Obtain lead foil with a purity of at least 99.5 % lead with a nominal thickness of 0.1 mm.

10.2.2 Obtain adhesive polyester or similar rigid plastic laminating plastic sheets with thickness between 0.1 and 0.25 mm for protecting samples.

10.2.3 For conditions where test samples are typically 0.6 mm lead equivalent or less:

10.2.3.1 Cut a series of six pieces each with a nominal thickness of 0.1 mm using the standard sample template.

10.2.3.2 Individually laminate three standards, one with one layer of lead foil, one with two, and one with three layers.

10.2.3.3 Weigh each sample and an empty laminating cover equivalent to the standards.

10.2.3.4 Determine the actual thickness (mm) of each sample as:

$$t = 10\frac{W_s - W_1}{A_s \rho_{Pb}} \quad (1)$$

Where W_s and W_1 are the weights of the laminated lead foil and the empty laminate cover respectively, A_s is the area of the sample in cm^2 and ρ_{Pb} is the density of lead (11.34 g/cm^3).

10.2.3.5 Number each standard and label each standard with actual thickness using an indelible marker (pen or pencil may damage sample).

10.2.3.6 Handle standards carefully and keep flat in a protective case to prevent damage.

11. Conditioning

11.1 There are no special conditioning requirements for this test.

12. Procedure

12.1 After documenting kV accuracy, measurement precision, and HVL:

12.1.1 Set the X-ray accelerating potential to the kilovoltage specified to simulate the scatter exposure.

12.1.2 Set field dimensions, aperture 4, ionization chamber, and sample clamping method according to Fig. 1.

12.1.3 Record exposure with no sample in the beam.

12.1.4 Record two exposures with the first sample in the X-ray beam. If exposure differs by more than 3 %, repeat with and without samples with a longer exposure time.

12.1.5 After each set of samples, record exposure with no sample in the beam; this exposure should not vary from pre-sample exposure by more than 3 %.

12.1.6 Use the same measurement procedure for lead standards (if not previously done).

13. Calculations

13.1 Calculate transmission as:

$$T = \frac{(E_{s1} + E_{s2})/2}{E_0} \quad (2)$$

Where E_{s1}, E_{s2}, and E_0 are the two exposure measurements through the sample and the measurement with no sample, respectively.

13.1.1 The protection rating is then given as:

$$P = 1 - T \quad (3)$$

13.2 Compute P values for all samples and for each lead standard thickness.

13.3 Determine P value for lead thicknesses of 0.25, 0.35, and 0.5 mm using linear interpolation of ln(P) using only three standards with P values nearest that of the desired lead thickness.

14. Report

14.1 State that the test method was conducted as directed in Test Method F3094.

14.2 Provide the following with each test set:

14.3 *Test Information*—Date of testing, place of testing, name of individual(s) performing the testing, equipment (manufacturer and model of X-ray generator and X-ray tube) used in testing, parameters (kV, HVL, tube current, and exposure time). Model and manufacturer of the kV monitoring device. Model and manufacturer of ionization chamber and electrometer, date of last calibration.

14.4 Protection ratings (P) may be reported for all scatter equivalent conditions in Table 1, at minimum the report should measure scatter equivalent conditions corresponding to primary X-ray beams generated at 80, 100, and 130 kV (measured using scatter equivalent beams at 70, 85, and 105 kV with appropriate filtration).

14.5 Report P values for lead standard thicknesses of 0.25, 0.35 and 0.5 mm. It is not recommended that lead equivalence be measured for all test materials. However, if lead equivalence is desired, the equivalence should be inferred from linear interpretation of ln(P) values using the three lead standards with P values closest to the measured value. P values for calibration should bracket the value of the test specimen, with at least one value below and one value above that of the test specimen.

14.5.1 Note that the protection ratings of common thicknesses of lead will not change, thus previously measured or published values may be substituted in the report.

15. Precision and Bias

15.1 Precision will depend on the uncertainty in the transmission measurement especially through thick materials yielding a small detector signal or in conditions where the output of the X-ray generator is not sufficiently reproducible. The described procedure should yield sufficient precision for practical use of this measurement. Care should be taken to ensure that generator settings do not exceed rated values for the X-ray tube.

15.2 There are no absolute standards for protection rating, however, because most users of protective garments are familiar with the protection provided by lead. The reporting of lead protection ratings similar to that of the test specimen will provide context.

16. Keywords

16.1 medical fluoroscopy; radiation protection; radiation protective clothing; X-ray; X-ray scatter

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