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USE OF PERSONAL MONITORS TO ESTIMATE EFFECTIVE DOSE EQUIVALENT AND EFFECTIVE DOSE TO WORKERS FOR EXTERNAL EXPOSURE TO LOW-LET RADIATION

Recommendations of the
NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS

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Preface

This Report is one of the series developed under the auspices of Scientific Committee 46, a scientific program area committee of the National Council on Radiation Protection and Measurements (NCRP) concerned with operational radiation safety. The Report provides practical recommendations on the use of personal monitors to estimate effective dose equivalent (H_E) and effective dose (E) for occupationally-exposed individuals. The Report is limited to external exposures to low-LET radiation. Recent additions to the radiation protection literature have made the recommendations possible. In order to avoid delay in utilizing the recommendations in the United States, the quantity H_E, as well as E, has been included until such time as the federal radiation protection guidance and associated implementing regulations are revised to express dose limits in E as recommended by the NCRP.

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1. Introduction

1.1 Background and Scope

In the United States, the current federal radiation protection guidance (EPA, 1987) and associated implementing regulations (NRC, 1991; DOE, 1993) include dose limits expressed as effective dose equivalent (H_E). The current National Council on Radiation Protection and Measurements (NCRP) radiation protection recommendations (NCRP, 1993) include dose limits expressed as effective dose (E). To monitor compliance with such dose limits correctly and fairly, practical monitoring data must be related to H_E or E.

In many external exposure circumstances, dose equivalent estimates obtained from personal monitors significantly overestimate H_E or E, particularly when the body is not uniformly irradiated due to the irradiation conditions or due to protective shielding of portions of the body. Specifically in these cases, the numerical relationships between monitoring data and H_E or E need to be better understood, so that appropriate monitoring practices are selected and monitoring data are properly evaluated.

This Report explores these numerical relationships for external exposure from low-LET radiation and gives recommendations that can be made at this time for estimating H_E or E in practice using personal monitors. In order to make progress in utilizing these recommendations in the United States, it is necessary to include numerical relationships for the quantity H_E, as well as E, until such time as the federal radiation protection guidance and associated implementing regulations are revised to express dose limits in E, as recommended by the NCRP.

Section 1 of the Report presents the quantities H_E and E and the relationship of each quantity to its corresponding radiation protection system. Section 2 describes the use of personal monitors for workers in the United States, including their calibration and how they are worn on individuals in various occupational settings. Section 3 discusses practical ways to use one or two personal monitors to obtain estimates of H_E and E. Section 4 provides the NCRP's recommendations on the use of personal monitors to obtain estimates of H_E and E that are conservatively safe for radiation protection purposes.

1.2 Effective Dose Equivalent and Effective Dose

1.2.1 *Use as a Quantity for Dose Limits*

When the entire body or parts of the body are irradiated externally, individual tissues and organs receive different absorbed doses. In order to relate the absorbed doses in tissue from nonuniform irradiation to radiation detriment in humans, a quantity is required which reflects the relative effects of different types of radiation and the relative radiosensitivity of the irradiated organs and tissues.

Contemporary radiation protection systems (ICRP, 1977a; 1991; NCRP, 1987; 1993) include dose limits expressed in such a quantity.[1] To obtain the quantity, absorbed doses are first multiplied by a *quality factor* (ICRP, 1977a) or a *radiation weighting factor* (ICRP, 1991), selected for the type and energy of the radiation incident upon the body, yielding, respectively, the *dose equivalent* in the tissue (ICRP, 1977a) or *equivalent dose* in the tissue (ICRP, 1991). Therefore:

- dose equivalent = quality factor × absorbed dose (ICRP, 1977a)
- equivalent dose = radiation weighting factor × absorbed dose (ICRP, 1991)

For low-LET radiation, the *quality factor* and *radiation weighting factor* have the value of one. Therefore, *dose equivalent* and *equivalent dose* have the same numerical value.

The *dose equivalent* or *equivalent dose* in tissue is then modified, respectively, by a *weighting factor* (ICRP, 1977a) or a *tissue weighting factor* (ICRP, 1991), which represents the relative contribution of the tissue or organ detriment to the total detriment, as if the whole body were uniformly irradiated. The sets of *weighting factors* (ICRP, 1977a) and *tissue weighting factors* (ICRP, 1991) differ in the tissues included and the numerical values of the respective factors. The weighted *dose equivalents* or *equivalent doses* for all tissues are summed to obtain the resulting quantity, called respectively,

[1]Section 1.1 states the need, at this time, for including both the *effective dose equivalent* and the *effective dose* in this Report.

the *effective dose equivalent* (ICRP, 1977a) or *effective dose* (ICRP, 1991). Therefore:

- effective dose equivalent = Σ (weighting factor × dose equivalent) (ICRP, 1977a)
- effective dose = Σ (tissue weighting factor × equivalent dose) (ICRP, 1991)

The unit of the quantity is the sievert (Sv), which is 1 J kg^{-1}. A commonly used subunit is the millisievert (mSv) or one one-thousandth of a Sv.

1.2.2 *Effective Dose Equivalent*

The effective dose equivalent (H_E) is the formulation for the weighted dose equivalents in irradiated tissues or organs stipulated in 1977 by the International Commission on Radiological Protection [ICRP (1977a)]. H_E is based on an ICRP analysis of the risk information in the 1977 report of the United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR (1977)]. The formulation is given in Table 1.1, where w_T is the weighting factor for the relative radiosensitivity of the tissue and H_T is the dose equivalent in the irradiated tissue or organ.

The w_T values given in Table 1.1 were developed by ICRP and were based on average cancer mortality risk coefficients for males and females ranging in age from 20 to 60 y (ICRP, 1977b) and average risk coefficients for hereditary effects, when account is taken of the proportion of exposure that is likely to be genetically significant. The weighting factors were considered applicable to both workers and the general public for radiation protection purposes.

The w_T values used in the formulation for H_E take into account only the mortality risks from cancer and the risk of severe hereditary effects (in the first two generations) associated with irradiation of the different tissues and organs. H_E is, therefore, a limited measure

TABLE 1.1—*Effective dose equivalent (H_E) (ICRP, 1977a).*

$H_E = \Sigma w_T H_T$	
Tissue (T)	w_T
Gonads	0.25
Breasts	0.15
Active bone marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30[a]

[a]0.06 for each of the five remaining tissues with highest H_T.

of radiation detriment. In 1977, the radiation detriment associated with H_E was 1.65 × 10^{-2} Sv^{-1} (*i.e.*, 1.25 × 10^{-2} Sv^{-1} for fatal cancers + 0.40 × 10^{-2} Sv^{-1} for severe hereditary effects in the first two generations) (ICRP, 1985).

1.2.3 *Effective Dose*

The effective dose (E) was presented in the 1990 recommendations of the ICRP (1991). E is a different formulation for the weighted equivalent doses for irradiated tissues or organs, developed by the ICRP from information presented in the 1990 report of the National Academy of Sciences' Committee on the Biological Effects of Ionizing Radiation [BEIR V (NAS/NRC, 1990)], the 1988 report of UNSCEAR (1988), and an analysis by Land and Sinclair (1991). The formulation is given in Table 1.2, where w_T is the tissue weighting factor for the relative radiosensitivity of the tissue and H_T is the equivalent dose[2] in the irradiated tissue or organ.

ICRP derived the w_T values given in Table 1.2 from a reference population of equal numbers of males and females having a wide

TABLE 1.2—*Effective dose (E) (ICRP, 1991).*

$E = \Sigma\, w_T H_T$

Tissue (T)	w_T
Gonads	0.20
Active bone marrow	0.12
Colon	0.12
Lungs	0.12
Stomach	0.12
Bladder	0.05
Breasts	0.05
Esophagus	0.05
Liver	0.05
Thyroid	0.05
Bone surfaces	0.01
Skin	0.01
Remainder[a]	0.05[b]

[a]The remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidneys, muscles, pancreas, spleen, thymus and uterus.

[b]If a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest equivalent dose in any of the tissues or organs for which a w_T is specified, a w_T of 0.025 should be applied to that tissue or organ and a w_T of 0.025 to the average equivalent dose in the rest of the remainder.

[2]The notation H_T is used by ICRP for both dose equivalent (ICRP, 1977a) and equivalent dose (ICRP, 1991).

range of ages. In the definition of E, the w_T values apply to workers, to the whole population and to either gender.

The w_T values in the formulation for E take into account not only the more recent estimates of mortality risks from cancer and the risk of severe hereditary effects (in all generations) for the irradiated tissues and organs, but also the risk of nonfatal cancer and the length of life lost if the effect occurs. It is, therefore, a more inclusive measure of radiation detriment. E is used in the most recent recommendations of the NCRP (1993), but has not yet been adopted as federal guidance or in associated implementing regulations in the United States. In 1990, the radiation detriment associated with E was 5.6×10^{-2} Sv^{-1} for a working population (*i.e.*, 4.0×10^{-2} Sv^{-1} for fatal cancers + 0.8×10^{-2} Sv^{-1} for nonfatal cancers + 0.8×10^{-2} Sv^{-1} for severe hereditary effects in all generations) (ICRP, 1991). The radiation detriment associated with E for the whole population was 7.3×10^{-2} Sv^{-1} (*i.e.*, 5.0×10^{-2} Sv^{-1} for fatal cancers + 1.0×10^{-2} Sv^{-1} for nonfatal cancers + 1.3×10^{-2} Sv^{-1} for severe hereditary effects in all generations) (ICRP, 1991).

1.2.4 *Consistency of Usage*

A particular set of values for tissue doses does not lead to the same numerical value for H_E and E. For example, assume a case in which the body is partially irradiated, the exposure is primarily to the chest, and the tissue doses are: breast, 2 mSv; lungs, 1 mSv; active bone marrow, 0.2 mSv; skin, 0.2 mSv; other specific tissues and remainder tissues, negligible. The resulting values are: H_E = 0.44 mSv and E = 0.25 mSv. For this reason, one cannot directly compare previous numerical values of H_E to current numerical values of E. Note also that a personal monitor located on the front at the chest would have indicated a dose equivalent in excess of 2 mSv, which is an overestimate of either H_E or E.

As a second example, consider a case in which the front of the body is irradiated by a nonuniform field of scattered radiation, the trunk is shielded by a protective apron on the front of the body, and the personal monitor value and tissue doses are as given in Table 1.3. The resulting values for H_E and E are 0.12 mSv and 0.05 mSv, respectively. In this case, the difference is caused primarily by the manner in which the remainder contribution is calculated (see Tables 1.1 and 1.2). Note also that a personal monitor located on the front at the neck outside and above the protective apron would have indicated a value of 1 mSv (see Table 1.3), which is a large overestimate of either H_E or E.

TABLE 1.3—*Personal monitor value and tissue doses for the second example in Section 1.2.4.*[a]

Personal Monitor or Tissue	mSv	
Personal monitor	1.00	(unshielded, outside and above the apron at the neck)
Thyroid	0.70	(unshielded by an apron)
Breasts	0.03	
Skin	0.03	
Esophagus, lungs	0.02	
Active bone marrow	0.01	
Bone surfaces	0.01	
Colon, stomach, bladder, liver	0.01	
Gonads	0.01	
Remainder tissues		
For calculation of E:		
average	0.10	
For calculation of H_E:		
adrenals	0.50	(unshielded by an apron)
brain	0.50	(unshielded by an apron)
salivary glands	0.50	(unshielded by an apron)
muscles	0.05	
all other remainder tissues	negligible	

[a]Irradiation of the front of the body by nonuniform field of scattered radiation, trunk shielded by protective apron on front of body.

Also, a dose limit expressed in the quantity H_E does not carry the same implications for radiation protection as a numerically equal dose limit expressed in the quantity E. For example, a value of H_E = 10 mSv and a value of E = 10 mSv do not carry the same implications for radiation detriment in a working population, as noted in Sections 1.2.2 and 1.2.3. One must be consistent in using H_E or E only in the context of its corresponding radiation protection system [*i.e.*, H_E with the ICRP (1977a) or the NRC (1991) systems; E with the ICRP (1991) or the NCRP (1993) systems].

2. Use of Personal Monitors for Workers in the United States

2.1 Calibration of Personal Monitors

2.1.1 *Deep Dose Equivalent or Personal Dose Equivalent for Strongly-Penetrating Radiation*

It is not practical in the work environment to measure the absorbed doses in the various organs and tissues necessary to compute H_E or E directly. Therefore, a number of quantitative relationships between H_E or E and various field or operational quantities have been developed and are available in the literature. The operational quantity named *personal dose equivalent*, $H_p(d)$, has been developed for the purpose of personal monitoring (ICRU, 1992), where d is the depth below a specified point on the body. For strongly-penetrating radiation, a depth of 10 mm is employed and the quantity is then specified as $H_p(10)$. The relationship between H_E or E and $H_p(10)$ is the most practical for use in determining H_E or E to workers for external exposure to low-LET radiation.

$H_p(10)$ can be estimated with a personal monitor which is worn at the surface of the body. The response of a personal monitor is calibrated for $H_p(10)$ under specific conditions by service laboratories that meet performance standards administered by accrediting organizations. $H_p(10)$ is synonymous with the quantity *deep dose equivalent* (NRC, 1991). The Nuclear Regulatory Commission (NRC) defines deep dose equivalent as the dose equivalent at a tissue depth of 1 cm (1,000 mg cm^{-2}). This definition permits the accrediting organizations to use various sizes and shapes of phantoms to assess this operational quantity.

2.1.2 *Accreditation Programs (National Voluntary Laboratory Accreditation Program and Department of Energy Laboratory Accreditation Program)*

In the United States, the National Voluntary Laboratory Accreditation Program (NVLAP) and the Department of Energy Laboratory

Accreditation Program (DOELAP) accredit organizations providing radiation monitoring services for occupationally exposed workers. The National Institute of Standards and Technology (NIST) within the U.S. Department of Commerce administers NVLAP, and the U.S. Department of Energy manages DOELAP. Each program grants accreditation to laboratories able to show technical competence through a proficiency test and an on-site assessment of facilities, staff qualifications and quality management systems.

Radiation monitoring laboratories seeking to achieve optimum proficiency test results with an accreditation standard must use calibration methods that duplicate or at least closely approximate the irradiation protocols described in the accreditation standard. This requirement is particularly important for calibrations using photons with energies below 200 keV where irradiation conditions must recreate the scattered radiation that contributes significantly to the response of the monitoring device.

Organizations required by the NRC or state regulatory agencies to monitor occupational radiation exposures must use laboratories or services accredited by NVLAP. Commercial laboratories obtain NVLAP accreditation as a business necessity. Organizations that operate their own monitoring laboratory must also gain NVLAP accreditation. Any laboratory can seek accreditation from NVLAP. Therefore, most nuclear power, education, health, industrial or military establishments conform to the performance test standard adopted by NVLAP in 1984, namely, the *American National Standard for Dosimetry—Personnel Dosimetry Performance—Criteria for Testing* (ANSI, 1983). The American National Standards Institute [ANSI (1983)] defines the deep dose equivalent as the dose equivalent at 1 cm depth in a 30 cm diameter sphere of soft tissue of a density of 1 g cm^{-3}.

In 1993, ANSI issued a revised version of this standard (ANSI, 1993). The 30 cm diameter sphere of soft tissue of density 1 g cm^{-3} was modified to a 30 cm × 30 cm × 15 cm slab of soft tissue with the composition defined by the International Commission on Radiation Units and Measurements [ICRU (1992)]. NVLAP and NRC have announced plans to use the revised version (NVLAP, 1994).

DOELAP accredits only the DOE and DOE contractor radiation monitoring programs. The special radiological environments associated with the Department's nuclear weapons responsibilities led DOE to develop a separate testing standard. The DOELAP performance test standard, namely, the *Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems* (DOE, 1986), defines deep dose equivalent at a depth of 1 cm in a slab phantom 30 cm × 30 cm × 15 cm simulating soft tissue containing trace elements normally found in the body. The trace elements increase the photon energy absorption cross sections for photons with energies less than 30 keV.

The differences between phantom size and shape influence the amount and angular distribution of radiation scattered within the phantom and out into the back of a monitoring device (Bartlett *et al.*, 1990). The amount of backscattered radiation peaks at nearly 70 percent of the incident radiation intensity for 75 keV photons. The amount decreases for lower energies to about 20 percent for 25 keV photons and for higher energies to about 10 percent for 662 keV photons. For photons with energies between 50 and 150 keV, the slab phantom produces approximately 10 percent more backscatter than the spherical shape. Therefore, under identical irradiation conditions involving photons in this energy range, these differences in backscatter result in the value of the deep dose equivalent being less at 1 cm depth in a sphere than at 1 cm depth in a slab.

The differences between the ANSI (1983) and DOE (1986) standards become most apparent for photons with energies between 30 and 100 keV. For the same irradiation condition, a monitoring device calibrated according to ANSI (1983) may yield values that differ by up to 20 percent from those obtained with a system calibrated according to DOE (1986) or ANSI (1993). The differences between the revised ANSI standard (ANSI, 1993) and the DOELAP standard are smaller because the specifications for the size and shape of the slab phantom are similar.

2.1.3 *Calibration Procedure and Limitations*

The NVLAP and DOELAP performance testing programs for personal monitors use nearly identical procedures, with the following features:

- Calibration of the intensities of the radiation fields is traceable to the NIST. The ionization chambers and electrometers used by the service laboratories to quantify the intensity of the radiation fields must be calibrated by the NIST or an accredited secondary standards laboratory. The intensity of the field is assessed in terms of air kerma or exposure (free-in-air), with the field collimated to minimize unwanted scatter. Conversion coefficients relate the air kerma or exposure (free-in-air) to the dose equivalent at a specified depth in a material of specified geometry and composition when the material is placed in the radiation field. The conversion coefficients vary as a function of photon energy, angle of incidence, and size and shape of backscatter medium.

The performance test standards used in the NVLAP and DOELAP programs list the applicable conversion coefficients.

- Personal monitors are irradiated to a known value of dose equivalent while mounted on a 30 cm × 30 cm × 15 cm slab of polymethylmethacrylate (PMMA). PMMA is an inexpensive and widely available material, but has a somewhat different density and yields somewhat different amounts of backscatter than a tissue equivalent material (Selbach *et al.*, 1989).
- The distance between the radiation source and the PMMA slab surface is large enough so that the radiation field approximates an aligned and expanded field (ICRU, 1992). An anterior to posterior radiation condition is simulated. The central ray of the radiation field is perpendicular to the center of the PMMA slab. Multiple personal monitors are irradiated to obtain information on accuracy and precision. Irradiation of the personal monitors using fields incident at nonperpendicular angles is used to examine differences from the response to the perpendicular irradiation.
- Linearity of the response of personal monitors is determined by delivering dose equivalents over the range of a few mSv to many Sv.
- A number of radiation fields spanning a range of radiation qualities are used to accommodate the range of radiation qualities encountered in the workplace.
- The calibration procedure provides a body of data about how the personal monitor responds to the various irradiation conditions. These data are converted into formulas or algorithms that generate a value for $H_p(10)$ for the irradiation conditions assumed in the workplace. The formulas or algorithms apply to the personal monitor system calibrated, and do not change unless there is a modification in the design or types of radiation detectors used in the personal monitor. An example of such a body of data for a particular monitoring device is provided by Ehrlich and Soodprasert (1994).
- Complete calibration of the personal monitors using the NIST secondary standards for all irradiation conditions is not done routinely. More often, the physical response of the components of the personal monitor is compared to the response of other calibrated radiation detection instruments to assess whether the personal monitor components respond the same as during complete calibration. This comparative calibration usually involves fewer radiation fields.

The irradiation conditions used during NVLAP and DOELAP performance testing are designed to be fully defined and reproducible.

They may differ, however, from the actual irradiation conditions experienced in the workplace. The disparity of irradiation conditions results in differences in response that cannot be fully simulated and represent basic limitations in the accuracy of personal monitors. Some of these limiting conditions are:

- The NIST radiation qualities are metrological standards and often differ from the radiation qualities that personal monitors encounter in the work environment, which often cannot be fully characterized. The NIST radiation fields for low-energy photons consist of bremsstrahlung spectra, each spectrum with a relatively wide distribution of photon energies. In the work environment, one often encounters discrete energies or a mixture of discrete energies emitted by various radionuclides. Some laboratories have supplemented the NIST radiation qualities with narrower photon energy bands. For example, the DOE includes irradiations using ^{241}Am.
- The calibration uses an aligned and expanded field incident in the anterior to posterior direction and perpendicular to the backscatter medium. The responses of personal monitors change as the irradiation angle changes and the effects of the backscatter medium become greater as the incident angle increases. NVLAP and DOELAP require performance information for irradiations at various angles of incidence and data on this angular response appear in the literature (Ehrlich and Soodprasert, 1994; Piltingsrud and Roberson, 1992; Plato *et al.*, 1988). Consequently, variations exist among laboratories in the degree to which angular response data are incorporated into the formulas and algorithms.
- The response of a personal monitor varies when worn on individuals of different sizes and shapes and when worn at different locations on the body (Jahr *et al.*, 1989; Wagner, 1989). Personal monitors showing good agreement when irradiated on a specific backscatter medium under calibration conditions might disagree when irradiated on another type of backscatter medium or on the body of an individual (Alberts *et al.*, 1989).
- The distance between the backscatter medium or body and the radiation detector elements in the holder of a personal monitor can also influence the response of the personal monitors. The backscatter fluence and resultant air kerma at the surface of a backscatter medium can decrease by a factor of two at a separation distance of 1 cm. Therefore, significant uncertainties can arise when the separation between personal monitor and the body surface varies during irradiation or differs from that used

during calibration. Apparently trivial issues such as a change in the type of clips used to attach personal monitors to clothing can also alter the response of the personal monitor (Bartlett *et al.*, 1989).

2.2 Number and Location of Personal Monitors on Individuals[3]

Current federal regulations limit the deep dose equivalent based on that part of the body likely to receive the highest exposure. If personal monitor results are not available or the personal monitor was not located at the position of highest exposure, the regulations allow the substitution of surveys and other radiation measurements (NRC, 1991). These requirements strongly influence the current practices in the United States for the number and location of personal monitors on individuals.

Many facilities use more than one personal monitor with one designated as the source of the data to be placed into the employee's permanent record for demonstrating compliance with the regulations. These personal monitors are designed to record exposures over periods of time, ranging from one to several months. Additional devices, such as direct-reading pocket ionization chambers or electronic monitoring devices, may be issued to monitor daily exposures. For situations in which the radiation field is not relatively uniform on the body, some facilities use multiple personal monitors. In that case, several personal monitors are attached to the clothing of the worker to document nonuniformity and to determine the location of highest exposure. In accordance with current federal regulations, the personal monitor result for the location of the worker's highest exposure is assigned as the deep dose equivalent in the employee's record.

The approaches taken in various work environments depend primarily on the type of facility and the activity being conducted. NCRP guidance on the use of personal monitors in these various work environments has appeared in a number of previous reports (NCRP, 1978a; 1978b; 1989a).

[3]This Section is limited to a general discussion on the number and location of personal monitors and other devices used to monitor deep dose equivalent. Other devices are commonly used to monitor dose equivalents in the extremities, skin and lens of the eye, for demonstrating compliance with the separate dose limits for deterministic effects in those tissues. These latter devices are not germane to this Report.

2.2.1 *Nuclear Power Industry*

Under normal conditions in the nuclear power industry, a single personal monitor is worn on the front of the chest, vertically positioned between the shoulders and the waist. However, usually more than one type of monitoring device is worn (*e.g.*, a personal monitor and a direct-reading pocket ionization chamber or electronic monitoring device) and all are attached to a necklace arrangement which places the monitoring devices in the center of the chest area. Most instructions require that the monitoring devices be worn together in an area about the size of an individual's hand, except when this is prevented by the size and weight of the device. Some utilities allow the worker to affix the direct-reading monitoring device to the arm around the biceps for easy viewing.

In addition, multiple personal monitors are often used for situations in which a worker is exposed to a nonuniform radiation field, in an attempt to assess the region of the body receiving the highest deep dose equivalent. Approaches to the use of multiple personal monitors vary widely, and the number used and their locations depend on the particular work activity. For example, during work inside a steam generator, where the radiation fields are potentially isotropic, a total of 12 to 14 personal monitors may be placed at specific locations on both the front and the back of the body, and on top of the head. In other work situations, when the radiation field may be relatively directional but variable (*e.g.*, during control-rod drive maintenance in a boiling-water reactor) the individual may wear all of the personal monitors at locations on the front of the body.

2.2.2 *Industrial Radiography*

A wide variety of irradiation conditions occur in industrial radiography, each irradiation condition depending on the nature of the work. Typically, the radiographer wears a direct-reading monitoring device to assess the daily exposure, an alarming monitoring device, unless an appropriate alarming device is already located in the work area, and a single personal monitor. The monitoring devices and personal monitor are normally worn in a region between the shoulders and the waist and are most likely to be worn in a pocket located in the chest region. The use of multiple personal monitors is not common in industrial radiography because the irradiation conditions associated with a particular task are generally well known.

2.2.3 *National Laboratories, Universities and Research Institutions*

National laboratories vary in their practices for the wearing of personal monitors. Some national laboratories incorporate the personal monitor into the security pass. In most cases, the laboratories have policies similar to those found in the nuclear power industry. That is, the personal monitor is attached to a necklace, placing the monitor essentially in the center of the chest, or the personal monitor is worn elsewhere between the shoulders and the waist.

Multiple personal monitors are used at national laboratories only in very special situations. At present, there does not appear to be a uniform approach.

Universities and research institutions also vary in their practices for wearing personal monitors. In typical situations, each individual is issued a single personal monitor and instructed orally to wear it at a location between the shoulders and the waist. These instructions are usually given in the initial employee training and are not found in laboratory procedures.

Around university research reactors, a number of monitoring devices may be worn, depending on the potential for mixed radiation fields. These facilities typically take the approach used in the nuclear power industry. That is, the personal monitor is used to provide the primary monitoring result, a direct-reading monitoring device is used to monitor the daily exposure of the worker, and other monitoring devices are used, if necessary, to assess neutron exposure. The monitoring devices are typically attached to a necklace and worn in the chest region. At many university reactors, proper wearing of monitoring devices is communicated as part of the general employee training and may also be found in facility procedures.

The use of multiple personal monitors is not common at universities and research institutions and, if necessary, would be implemented on an *ad hoc* basis.

2.2.4 *Medical Institutions*

2.2.4.1 *Clinical Staff Not in Proximity of Patient Undergoing a Procedure.* Most often, clinical staff perform tasks that do not require them to be near a patient undergoing common procedures in diagnostic radiography, during most nuclear medicine procedures, or during teletherapy. For these workers, a single personal monitor is located on the trunk of the worker (*i.e.*, at the neck, chest, waist or pants pocket). This practice is fairly uniform throughout the United States.

Staff preparing radiopharmaceuticals to be administered for nuclear medicine diagnostic and therapeutic procedures and handling sealed sources for brachytherapy use protective blocks to shield the head and trunk. For these workers, a single personal monitor is located on the trunk.[4]

2.2.4.2 *Clinical Staff in Proximity of Patient Undergoing a Procedure.* Clinical staff may perform tasks that require them to be near a patient during a procedure (*e.g.*, during diagnostic or interventional fluoroscopy, during mobile radiography, while attending a patient during diagnostic radiography or nuclear medicine procedures, and while caring for a patient undergoing brachytherapy or nuclear medicine therapy procedures). Staff working with nuclear medicine therapy patients may use shielding devices, such as vial and syringe shields, when administering radiopharmaceuticals to patients. In procedures involving diagnostic or interventional fluoroscopy, staff typically wear protective aprons having a recommended amount of lead equivalence, so that much of the trunk of the body is shielded from radiation. The apron may cover only the front of the individual or it may also cover the back. Staff performing or assisting in interventional procedures using fluoroscopy also may wear protective thyroid shields, or use other mobile shielding devices interposed between the staff and the patient. By contrast, staff working with nuclear medicine or therapy patients do not wear protective aprons.

For many situations where protective aprons are worn, the exposure is primarily to the front of the individual. Under these circumstances, a personal monitor located under the apron on the trunk of the individual indicates the dose equivalent to the shielded trunk of the body, and unshielded parts of the body may receive higher exposure. A monitor located outside and above the apron indicates the dose equivalent to the unshielded parts of the body.

For some situations, such as certain nursing procedures, individuals may work part of the time with their backs to the patient while wearing an apron that covers both the front and the back. For irradiation to the back, a personal monitor located on the back under such an apron indicates irradiation of the shielded trunk of the body; some unshielded parts of the body may receive higher exposures. A monitor that is located on the front under such an apron is shielded

[4]In the industrial manufacturing and distribution of radionuclides and radiopharmaceuticals, personal monitors may be located in the neck or chest region, sometimes along with a direct-reading monitoring device.

additionally by the individual's body. A monitor located on the front outside and above the apron indicates the dose equivalent after attenuation by both the individual's body and reduction of radiation scattered from the parts of the body under the apron.

Practices differ throughout the United States. Sometimes a single personal monitor is used. Sometimes two personal monitors are used, one under an apron and one outside and above the apron.

3. Estimating Effective Dose Equivalent or Effective Dose in Practice Using Personal Monitors

The principal data available to determine H_E or E directly from $H_p(10)$ are conversion coefficients which give the quotient of H_E or E and $H_p(10)$ [*i.e.*, $H_E/[H_p(10)]$ or $E/[H_p(10)]$]. The unit for each of the three quantities is Sv; therefore, these conversion coefficients are dimensionless. Such conversion coefficients have been derived from calculations for a number of idealized conditions for irradiation by monoenergetic photons of mathematically described reference adult anthropomorphic phantoms. The conversion coefficients are a function of photon energy, photon beam direction, surface of the phantom on which the radiation is incident, and location where $H_p(10)$ is being evaluated on the phantom.

To use these conversion coefficients directly in practice, one would need to be able to characterize the irradiation conditions in the workplace for a particular situation with regard to the following factors:

- the nominal photon energy, energy range or energy distribution of the radiation field
- the nominal direction of the radiation field with respect to the worker, and the surface of incidence of the radiation field on the worker
- the location where $H_p(10)$ is being evaluated on the worker

If the irradiation conditions for a particular situation require characterization with more than one radiation field, the factors listed above would need to be identified for each field that is distinctly different. In addition, some knowledge of the relative contribution of each field to the sum of the irradiation is needed. This is seldom achieved in practice.

For those irradiation conditions for which the conversion coefficients are close to a value of 1.0, the value of $H_p(10)$ recorded by an appropriately placed personal monitor is a practical surrogate for H_E or E. This case is explored in Section 3.1.

For those situations in which irradiation conditions cannot be known with confidence or the conversion coefficients are not close to a value of 1.0, an empirical approach involving two personal monitors is required. This case is explored in Section 3.2.

3.1 Use of Personal Dose Equivalent for a Strongly-Penetrating Radiation Value Determined with One Personal Monitor as a Surrogate for Effective Dose Equivalent or Effective Dose

Figure 3.1 reproduces the conversion coefficients provided in ICRU (1988) for $H_E/[H_p(10)]$. For these conversion coefficients, $H_p(10)$ was approximated by the dose equivalent at a depth 10 mm along an appropriate radius (*i.e.*, the central axis) in the ICRU sphere (ICRU, 1988). Conversion coefficients are given for personal monitors located on the body at the center of the chest (*i.e.*, the front) or the center of the back (*i.e.*, the back) for the following irradiation geometries:

- Personal monitor located on the front of the body (*i.e.*, at the center of the chest)
  - AP, broad parallel beam from front to back (anterior to posterior)
  - PA, broad parallel beam from back to front (posterior to anterior)
  - LAT, broad parallel beam from either side (lateral)
  - IS, isotropic field
  - PL.IS, planar isotropic field, perpendicular to body axis
- Personal monitor located on the back of the body (*i.e.*, at the center of the back)
  - AP, broad parallel beam from front to back (anterior to posterior)
  - PA, broad parallel beam from back to front (posterior to anterior)

The AP, PA, LAT and PL.IS irradiation geometries are illustrated in Figure 3.2. They simulate broad unidirectional fields of infinite extent, with the fields at right angles to the long axis of the body (*i.e.*, plane parallel fields). The AP, PA and LAT geometries approximate irradiation patterns for a person whose orientation is fixed relative to a radiation source. The planar isotropic (PL.IS) geometry is created by rotating the body about its long axis at a uniform rate in a broad unidirectional field at right angles to the axis of rotation. The isotropic (IS) geometry (not shown in Figure 3.2) simulates a

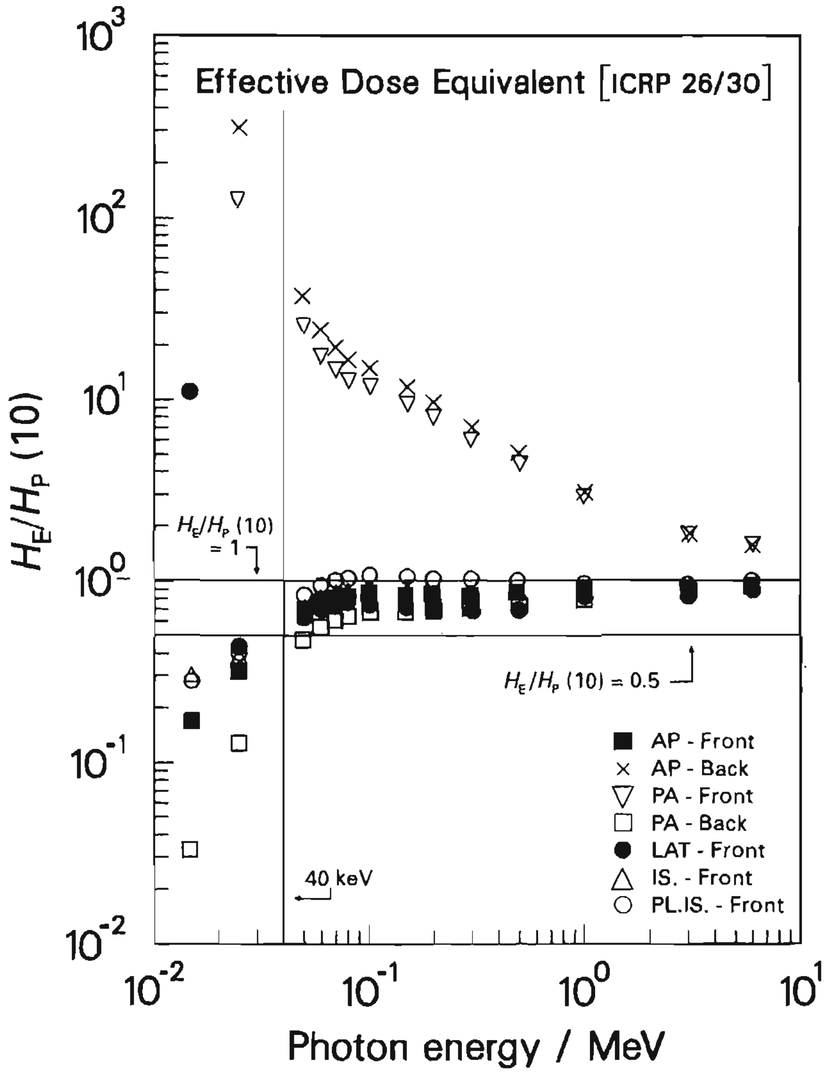

Fig. 3.1. Ratio of H_E to $H_p(10)$ as a function of photon energy. $H_p(10)$ is approximated by the dose equivalent at depth 10 mm along the central axis in the ICRU sphere (ICRU, 1988). Five geometries and two locations for the personal monitor are considered in the calculations (see Section 3.1) (adapted from ICRU, 1988 and reproduced with permission).

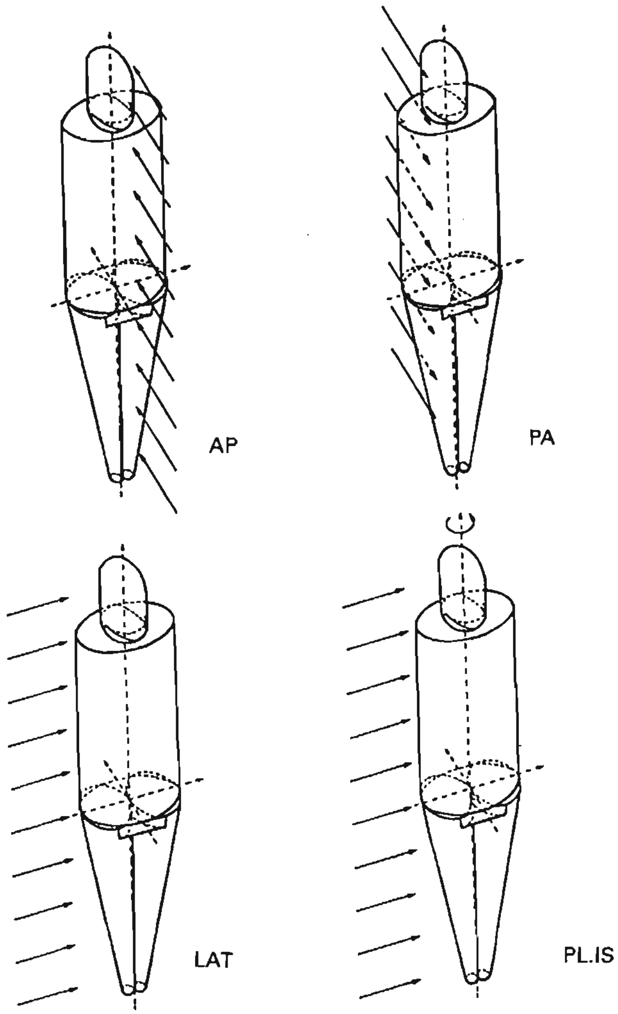

Fig. 3.2. Illustration of AP, PA, LAT and PL.IS irradiation geometries (see Section 3.1) (adapted from ICRP, 1987 and reproduced with permission).

radiation field in which the photon fluence per unit solid angle is the same for all directions. The PL.IS and IS geometries approximate irradiation patterns for a person moving around unsystematically relative to a radiation source.

If one draws horizontal lines on Figure 3.1 at $H_E/[H_p(10)] = 1$ (*i.e.*, where the two quantities are numerically equal) and $H_E/[H_p(10)] = 0.5$ [*i.e.*, where $H_p(10)$ is equal to 2 H_E], then the region between and including the two horizontal lines is one where $H_p(10)$, when used directly, does not underestimate the value of H_E, and does not overestimate the value of H_E by more than a factor of two. These are conservatively safe criteria for radiation protection purposes.

This region encompasses the conversion coefficients for the following irradiation geometries and the indicated locations of the personal monitor, provided the photon energy is greater than about 40 keV (about 50 keV for the PA irradiation geometry listed):

- Personal monitor located on the front
  - AP, broad parallel beam from front to back (anterior to posterior)
  - LAT, broad parallel beam from either side (lateral)
  - IS, isotropic field
  - PL.IS, planar isotropic field, perpendicular to body axis (except for a slight underestimate of H_E in the region of 100 to 200 keV)
- Personal monitor located on the back
  - PA, broad parallel beam from back to front (posterior to anterior)

In practice, if one knows that the actual conditions in the workplace can be reasonably simulated by these idealized irradiation geometries and locations of the personal monitor, and the photon energy is within the indicated range, $H_p(10)$ can be used directly as a surrogate for H_E even if the precise conditions are not known. The most frequently encountered condition of AP irradiation with the personal monitor located on the front of the body is well within this region for photon energies above 40 keV, and use of $H_p(10)$ would not overestimate H_E by more than a factor of three for photon energies as low as 30 keV.

For energies less than about 30 keV for all irradiation geometries, and for PA and AP irradiation geometries where the personal monitor is located on the side of the body opposite to the incident photons, $H_p(10)$ can severely under- or overestimate H_E as indicated in Figure 3.1.

ICRU and ICRP currently have a joint effort underway to review and present similar conversion coefficients for E, but that work is not yet published. When conversion coefficients are published, a similar evaluation of the irradiation conditions for which $H_p(10)$ determined with one personal monitor will be a practical surrogate for E will be possible.

3.2 Use of Personal Dose Equivalent for Strongly-Penetrating Radiation Values Determined from Two Personal Monitors to Estimate Effective Dose Equivalent or Effective Dose

In scenarios for which the irradiation geometry in practice is difficult to determine, investigators have recommended the use of $H_p(10)$ values determined from multiple personal monitors to obtain improved estimates of H_E (Lakshmanan *et al.*, 1991; Xu, 1994). These investigators have demonstrated that $H_p(10)$ values from personal monitors placed on the front (*i.e.*, center of the chest) and back (*i.e.*, center of the back) of individuals can be combined in specific algorithms that yield closer estimates of H_E than the values of $H_p(10)$ used separately. In this Report, the NCRP also evaluates this approach independently.

These analyses require that the $H_p(10)$ values for normal incidence be modified for irradiation geometries where the field is incident other than perpendicular to the surface of the personal monitor. The methods used in developing these modifications to $H_p(10)$ for non-normal incidence included extensive Monte Carlo calculations of photon interactions in anthropomorphic phantoms (Xu, 1994) or in PMMA and tissue slabs and the ICRU sphere (Grosswendt, 1991; Grosswendt and Hohlfeld, 1982), and thermoluminescent dosimeter measurements in water cubes (Lakshmanan *et al.*, 1991). Some of these modifications for $H_p(10)$ are presented in ICRU (1992).

The algorithm preferred by Lakshmanan *et al.* (1991) was the sum of the values of $H_p(10)$ for the two personal monitors divided by 1.5:

$$H_E\ (\text{estimate}) = \frac{H_p(10)_{\text{front}} + H_p(10)_{\text{back}}}{1.5} \qquad (3.1)$$

which, for a number of irradiation geometries and photon energies between 30 keV and 1.25 MeV, yielded closer estimates of H_E than use of $H_p(10)$ for the personal monitor on the front alone. Lakshmanan *et al.* (1991) obtained $H_p(10)$ values through measurements in a 30 cm cubic water phantom. For PA irradiation, where the personal monitor on the front is opposite from the surface of incidence, the $H_p(10)$ values are much lower than observed by investigators using slab phantoms 15 cm thick or anthropomorphic phantoms 20 cm thick, but similar to the values obtained using the 30 cm ICRU sphere.

The algorithm preferred by Xu (1994) weighted the $H_p(10)$ values for the two personal monitors as follows:

$$H_E \text{ (estimate)} = \frac{H_p(10)_{\text{maximum of front or back}} + H_p(10)_{\text{average of front and back}}}{2} \quad (3.2)$$

Xu (1994) explored three photon energies (*i.e.*, 80 keV, 300 keV and 1 MeV) and a number of irradiation geometries, including geometries with a large range of non-normal incidence. In particular, Xu (1994) provided H_E (estimate) values for a variety of point sources at various locations and distances from the body. Xu (1994) computed the $H_p(10)$ values in tissue-equivalent spheres located on the relevant surface of the anthropomorphic phantom.

In this Report, the NCRP uses the published $H_p(10)$ modification factors for PMMA slabs (Grosswendt, 1991) and the conversion coefficients tabulated in ICRP (1987) to calculate conversion coefficients for $H_E/[H_p(10)]$ for a variety of irradiation geometries and a number of photon energies between 30 keV and 1 MeV. This Report also develops two alternative algorithms which weight the $H_p(10)$ values for the two personal monitors depending on the desired objective, as follows:

Alternative (1)

$$H_E \text{ (estimate)} = 0.7\ H_p(10)_{\text{front}} + 0.3\ H_p(10)_{\text{back}} \quad (3.3)$$

This alternative is denoted the (70/30) algorithm and it minimizes the differences of the ratios of H_E (estimate)/H_E from the value of 1.0. That is, if both under- and overestimates of H_E are equally acceptable in practice, this algorithm provides the minimal spread of these estimates around the H_E values. A Monte Carlo method was utilized to obtain the optimum weighting factors (*i.e.*, 0.7 and 0.3) for the $H_p(10)$ values of the two personal monitors, with the sum of the weighting factors constrained to be equal to 1.0 (Claycamp, 1996).

Alternative (2)

$$H_E \text{ (estimate)} = 0.55\ H_p(10)_{\text{front}} + 0.50\ H_p(10)_{\text{back}} \quad (3.4)$$

This alternative is denoted the (55/50) algorithm and it provides the optimum distribution of ratios of H_E (estimate)/H_E such that the number of estimates of H_E that are less than 0.9 H_E are minimal. That is, the (55/50) algorithm best avoids underestimating H_E by more than 10 percent, but at the cost of sometimes allowing larger overestimates of H_E than the (70/30) algorithm. A commercial nonlinear optimization method (Quattro Pro®)[5] was utilized to obtain

[5]Novell, Inc., 1555 N. Technology Way, Orem, Utah 84057-2399.

the optimum weighting factors (*i.e.*, 0.55 and 0.50) for the $H_p(10)$ values of the two personal monitors, with the constraint that $0.9 < H_E$ (estimate)/$H_E < 2.5$. There was no constraint on the sum of the weighting factors.

The results using H_E (estimate) derived from the preferred algorithms of Lakshmanan *et al.* (1991) and Xu (1994) and both algorithms of NCRP for various irradiation geometries are tabulated in Table 3.1. The results using $H_p(10)$ values for a personal monitor on the front as the H_E (estimate), and using the average of the $H_p(10)$ values for personal monitors on the front and back as the H_E (estimate) are also tabulated in Table 3.1. Included for comparison in the column for "front only" are the values from ICRU (1988) that were shown earlier in Figure 3.1, and which use $H_p(10)$ values obtained in a 30 cm ICRU sphere (Grosswendt and Hohlfeld, 1982). The table entries are given as H_E (estimate)/H_E, where H_E (estimate) is the value obtained by the respective algorithm and H_E is a value generated from the relevant Monte Carlo simulations.[6]

The useful criteria introduced earlier for radiation protection purposes are that the estimate of H_E should: (1) not be much less than the actual H_E [*i.e.*, H_E(estimate)/H_E between 0.9 and 1.0] to avoid underestimating H_E by much, and (2) not be much higher than the actual H_E [*i.e.*, H_E (estimate)/H_E not much greater than 2.0 to 3.0] to avoid seriously overestimating H_E. How the various results in Table 3.1 compare to these criteria for each irradiation geometry and algorithm is summarized in Table 3.2.

The preferred algorithms of Lakshmanan *et al.* (1991), Xu (1994) and both algorithms of the NCRP generally meet the criteria, with occasional exceptions. It should also be noted that the results from Xu (1994) indicate that the Xu (1994) algorithm is applicable for point sources (see Footnote "c" in Table 3.1).

The preferred algorithm of Lakshmanan *et al.* (1991) and the (55/50) algorithm of the NCRP most consistently meet the criteria and cover a wide range of photon energies. However, the (55/50) algorithm of the NCRP has two practical advantages:

1. The values of H_E (estimate) are obtained from values of $H_p(10)$ consistent with the calibration procedures for personal monitors used in the United States (*i.e.*, a 30 × 30 × 15 cm PMMA slab), and

[6]The Monte Carlo simulations for H_E in ICRP (1987) were used for the H_E (estimate)/H_E values reported in ICRU (1988) and most cases for both Lakshmanan *et al.* (1991) and the NCRP. The Monte Carlo simulations for H_E in Xu (1994) were used for the H_E (estimate)/H_E values reported in Xu (1994) and the overhead and underfoot cases for both Lakshmanan *et al.* (1991) and the NCRP.

TABLE 3.1— *Ratio of H_E (estimate) to H_E for various irradiation geometries and combinations of $H_p(10)$ values from personal monitors located on the front and back of an individual.*

Irradiation Geometry	Photon Energy (MeV)	Front Only: IC88[b]	Front Only: La91[b]	Front Only: Xu94[b]	Front Only: NCRP[b]	Authors' Preferred Algorithms[a]: La91	Authors' Preferred Algorithms[a]: Xu94[c]	Authors' Preferred Algorithms[a]: NCRP (70/30)	Authors' Preferred Algorithms[a]: NCRP (55/50)	Average for Front and Back: La91	Average for Front and Back: Xu94	Average for Front and Back: NCRP
AP	0.030	2.39	2.10	—	2.75	1.40	—	1.96	1.56	1.05	—	1.43
	0.046	1.57	1.55	—	1.77	1.05	—	1.32	1.11	0.79	—	1.02
	0.065	1.24	1.44	—	1.48	0.99	—	1.14	0.98	0.74	—	0.91
	0.080	1.18	1.47	1.14	1.40	1.01	0.89	1.08	0.95	0.76	0.63	0.87
	0.105	1.15	1.44	—	1.34	1.01	—	1.05	0.91	0.76	—	0.86
	0.300	1.16	1.29	1.25	1.23	0.98	1.02	1.00	0.91	0.74	0.79	0.85
	1.00	1.11	1.14	1.23	1.14	0.96	1.05	0.99	0.95	0.72	0.87	0.89
	1.25	1.11	1.11	—	—	0.95	—	—	—	0.72	—	—
PA[d]	0.030	0.012	<0.01	—	0.21	2.87	—	1.83	2.93	2.15	—	2.91
	0.046	0.046	0.043	—	0.40	1.65	—	1.10	1.58	1.24	—	1.57
	0.065	0.070	0.057	—	0.46	1.35	—	0.94	1.27	1.01	—	1.26
	0.080	0.076	0.058	0.17	0.47	1.30	1.05	0.88	1.17	0.98	0.76	1.15
	0.105	0.084	0.097	—	0.46	1.27	—	0.83	1.10	0.96	—	1.08
	0.300	0.18	0.17	0.39	0.55	1.16	1.25	0.83	1.04	0.88	0.96	1.02
	1.00	0.34	0.31	0.56	0.70	1.05	1.17	0.87	1.02	0.79	0.97	0.98
	1.25	0.43	0.35	—	—	1.03	—	—	—	0.78	—	—
LAT	0.030	2.17	3.17	—	4.20	4.78	—	4.20	4.41	3.59	—	4.20
	0.046	1.67	2.04	—	1.68	2.59	—	1.68	1.77	1.95	—	1.68
	0.065	1.35	1.89	—	1.17	2.13	—	1.17	1.23	1.60	—	1.17
	0.080	1.33	1.29	1.82	1.06	2.05	1.84	1.06	1.12	1.54	1.83	1.06
	0.105	1.35	1.38	—	1.04	1.95	—	1.04	1.09	1.47	—	1.04
	0.300	1.47	1.37	2.10	0.98	1.63	2.11	0.98	1.03	1.22	2.11	0.98
	1.00	1.28	1.38	1.76	0.82	1.27	1.80	0.82	0.86	0.95	1.79	0.82
	1.25	1.22	1.35	—	—	1.27	—	—	—	0.95	—	—

TABLE 3.1— *Ratio of H_E (estimate) to H_E for various irradiation geometries and combinations of $H_p(10)$ values from personal monitors located on the front and back of an individual.* (continued)

Irradiation Geometry	Photon Energy (MeV)	H_E (estimate)/H_E										
		Front Only				Authors' Preferred Algorithms[a]				Average for Front and Back		
								NCRP				
		IC88[b]	La91[b]	Xu94[b]	NCRP[b]	La91	Xu94[c]	(70/30)	(55/50)	La91	Xu94	NCRP
Overhead[e]	0.080	—	3.41	2.25	1.95	2.27	2.24	1.95	2.05	3.41	2.24	1.95
	0.300	—	3.67	2.49	1.78	2.45	2.48	1.78	1.87	3.67	2.47	1.78
	1.00	—	3.03	2.04	1.40	2.02	2.04	1.40	1.46	3.03	2.03	1.40
Underfoot[e]	0.080	—	4.26	3.61	2.44	1.84	3.60	2.44	2.56	4.26	3.57	2.44
	0.300	—	4.39	3.66	2.13	2.93	3.65	2.13	2.23	4.39	3.64	2.13
	1.00	—	3.96	3.35	1.83	2.64	3.34	1.83	1.92	3.96	3.33	1.83

[a]Authors' preferred algorithms for estimating H_E from the $H_p(10)$ values for the front and back personal monitors (see Section 3.2).

[b]Abbreviations for references: IC88 (ICRU, 1988); La91 (Lakshmanan *et al.*, 1991); Xu94 (Xu, 1994); NCRP (this Report).

[c]Xu (1994) also provided H_E (estimate)/H_E values for 0.08, 0.3 and 1.0 MeV for a variety of point sources at various locations and distances from the body, which are not included in this Table. The values for the Xu94 preferred algorithm for 10 different point-source geometries ranged from a low of 0.80 to a high of 2.22.

[d]The water phantom used by Lakshmanan *et al.*, (1991) was 30 cm thick. Therefore, the "front only" values for PA irradiation are much lower than observed by the other investigators using phantoms with thicknesses of 15 or 20 cm, but similar to the "front only" values of ICRU (1988) which used the 30 cm ICRU sphere.

[e]The overhead geometry is simulated by plane parallel fields directly above and at small angles to the long axis of the body; the underfoot geometry is simulated by a plane parallel field directly beneath the long axis of the body (Xu, 1994).

TABLE 3.2—*Comparison of H_E(estimate)/H_E values from Table 3.1 to criteria for radiation protection purposes.*[a]

Irradiation Geometry	H_E(estimate)/H_E					
		Authors' Preferred Algorithm				
				NCRP[b]		
	Front Only	La91[b]	Xu94[b]	(70/30)	(55/50)	Average for Front and Back
AP	Meets	Meets	Meets[d]	Meets	Meets	Generally underestimates
PA	Underestimates	Meets	Meets[d]	Some underestimates	Meets	Some underestimates (La91, Xu94); meets (NCRP)
LAT	Generally meets	Generally meets	Meets[d]	Generally meets	Generally meets	Generally meets
Overhead[c,d]	Meets (Xu94, NCRP); overestimates (La91)	Meets	Meets	Meets	Meets	Overestimates (La91); meets (Xu94, NCRP)
Underfoot[c,d]	Meets (NCRP); overestimates (Xu94, La91)	Meets	Overestimates	Meets	Meets	Overestimates (La91, Xu94); meets (NCRP)

[a]Criteria: H_E(estimate)/H_E not much greater than 2.0 to 3.0; H_E(estimate)/H_E between 0.9 and 1.0 [i.e., H_E (estimate) not much less than H_E].
[b]Abbreviations for references: La91 (Lakshmanan *et al.*, 1991); Xu94 (Xu, 1994); NCRP (this Report).
[c]The overhead geometry is simulated by plane parallel fields directly above and at small angles to the long axis of the body; the underfoot geometry is simulated by a plane parallel field directly beneath the long axis of the body (Xu, 1994).
[d]Data available only for 0.08, 0.3 and 1.0 MeV.

2. The algorithm was optimized to meet the conservatively safe radiation protection criteria introduced earlier.

These advantages support the general use of the NCRP (55/50) algorithm:

$$H_E \text{ (estimate)} = 0.55\ H_p(10)_{front} + 0.50\ H_p(10)_{back}. \qquad (3.5)$$

ICRU and ICRP have a joint effort underway to review and present values of E for Monte Carlo calculations in anthropomorphic phantoms, but that work is not yet published. When the data are published, a similar evaluation of the use of $H_p(10)$ values determined from two personal monitors to estimate E will be possible.

3.3 Specific Approach When Protective Aprons Are Worn During Diagnostic and Interventional Medical Procedures Using Fluoroscopy

3.3.1 *Unique Considerations*

Clinical staff taking part in diagnostic and interventional procedures using fluoroscopy wear protective aprons to shield internal tissues and organs in the torso from scattered x rays.[7] Use of the measurements from monitoring devices worn outside and above protective aprons as the record of H_E or E for these individuals results in significant overestimates of their actual risk.

The current situation is exemplified by a study of clinical staff exposures in cardiac angiography at the Montreal Heart Institute (Renaud, 1992). Extensive measurements of staff exposures were made using thermoluminescent dosimeters (TLDs) for 15,000 procedures in three cardiac catheterization laboratories over a 5 y period (1984 to 1988). The TLDs were located under the protective apron at the waist and at the collar outside and above the apron. Readings were made at three-month intervals, with a minimum reportable value of 0.2 mSv. Average values (in mSv per y) for various groups of staff, based on measurements with TLDs worn at the collar, are given in Table 3.3.

Physicians had the highest group average at 20 to 30 mSv per y, with the potential for some physicians, particularly those in training, to be assigned numerical values greater than the dose limit of 50 mSv per y if the results of the TLD on the collar are recorded as

[7]NCRP recommends the use of protective aprons that are at least 0.5 mm lead equivalent (NCRP, 1989b).

H_E or E. On the other hand, the TLD at the waist under the protective apron rarely measured more than the minimum reportable value of 0.2 mSv for a calendar quarter.

Other uses of fluoroscopy would have the potential for higher cumulative collar exposures. For example, abdominal interventional and angiography procedures typically use image intensifiers and x-ray field sizes which are larger than those used in a cardiac catheterization laboratory. Depending on the orientation of the primary beam, the scattered radiation from the patient may have greater intensity in these other clinical situations than in a cardiac catheterization laboratory.

For example, in a study group of 28 interventional radiologists from a number of institutions, the mean cumulative value estimated for a year was 48 mSv for the personal monitor worn on the collar outside and above the protective apron (with a range of 3.2 to 115 mSv), and 0.9 mSv for a personal monitor worn under the apron (with a range of 0.2 to 4.1 mSv). The radiologists wore both personal monitors for approximately two months. The predicted cumulative annual values were estimated based on the amount of time each spent performing interventional radiology procedures, which varied between 25 to 100 percent of the time for a given radiologist (Niklason *et al.*, 1993).

The results from the Montreal Heart Institute (Renaud, 1992) and Niklason *et al.* (1993) illustrate the problem of using a single personal monitor worn outside and above the protective apron on the collar to assess H_E and E. When such readings are interpreted as the quantity H_E or E, without taking account of the deliberate protection afforded by a protective apron, it can appear that physicians are receiving large fractions of, or exceeding the numerical value of, the prescribed dose limit, when, in fact, this is not the case. This practice does not evaluate the relevant dose to the individual. Therefore, a method for converting personal monitor readings to the quantities H_E or E is required.

The Conference of Radiation Control Program Directors (CRCPD) recognized this need to convert personal monitor readings to H_E

TABLE 3.3—*Clinical staff exposures in cardiac angiography. Group averages (in mSv per y) based on measurements with TLDs worn on the collar outside and above protective aprons (Renaud, 1992).*

Group	mSv per y
Physicians	20 to 30[a]
Nurses	8 to 16
Technologists	2
Assistant technicians	0 to 2

[a]The range of annual values for individual physicians was 2 to 60 mSv per y.

specifically for clinical staff performing fluoroscopy procedures and wearing protective aprons. The Conference has included provisions for this conversion in the current revisions of its *Suggested State Regulations for the Control of Radiation* (CRCPD, 1995), a document which contains model regulations for voluntary use by state authorities. The applicable provisions[8] are: "When a protective apron is worn while working with medical fluoroscopic equipment and monitoring is conducted as specified . . ., the [H_E] for external radiation shall be determined as follows:

"1. When only one individual monitoring device is used and it is located at the neck outside the protective apron, the reported deep dose equivalent shall be the [H_E] for external radiation; or

"2. When only one individual monitoring device is used and it is located at the neck outside the protective apron, and the reported dose exceeds 25 percent of the limit specified . . ., the reported deep dose equivalent value multiplied by 0.3 shall be the [H_E] for external radiation; or

"3. When individual monitoring devices are worn, both under the protective apron at the waist and outside the protective apron at the neck, the [H_E] for external radiation shall be assigned the value of the sum of the deep dose equivalent reported for the individual monitoring device located at the waist under the protective apron multiplied by 1.5 and the deep dose equivalent reported for the individual monitoring device located at the neck outside the protective apron multiplied by 0.04."

Provision 1 is a continuation of current practice, but is used only when the reported deep dose equivalent does not exceed 25 percent of the specified limit. Provision 2 comes from application of a previous observation by NCRP (1978c) in conjunction with the proposal by Webster (1989) noted below. The observation was that exposure of the face and neck will exceed the exposure recorded under the apron by factors between 6 and 27. Using the smallest value in the range (*i.e.*, a factor of six) and the formula of Webster (1989), the result is the value of 0.3. Provision 3 comes from application of a proposal by Webster (1989) for the use of two monitoring devices, based on the experimental data of Faulkner and Harrison (1988). The proposal of Webster (1989) is discussed in Section 3.3.3. However, more recent information is available from which to derive conversions for both H_E and E from personal monitor values of $H_p(10)$. The current NCRP recommendations using this additional information are developed in Sections 3.3.2, 3.3.3 and 3.3.4.

[8]These provisions are found in Part D, Sec. D. 201, c., ii of CRCPD (1995).

3.3.2 *Derivation of Effective Dose Equivalent and Effective Dose from Personal Monitor Values of Personal Dose Equivalent for Strongly-Penetrating Radiation*

Extensive experimental measurements have been performed that simulate the irradiation of clinical staff for conditions commonly encountered in fluoroscopy (Faulkner and Harrison, 1988; Faulkner and Marshall, 1993).

In this work, x-ray scatter radiation was produced at various x-ray tube potentials in the range of 60 to 120 kVp, with the x-ray tube in the over- or undertable position. Dose equivalents for clinical staff were determined using film badges placed at four or five locations, including the neck and waist, on a Rando phantom. Absorbed doses to tissues and organs, when a protective apron was not present, were determined using numerous TLDs in the phantom and auxiliary data from the literature when necessary. Absorbed doses to the tissues, when a protective apron was present, were estimated from the absorbed doses without an apron, as modified by transmission data for the appropriate x-ray tube potential and equivalent lead thickness. H_E and E were computed for the noted range of x-ray tube potentials without a protective apron and for protective aprons with thicknesses from 0.1 to 0.5 mm lead equivalent, at intervals of 0.05 mm.

The dose equivalents in Faulkner and Harrison (1988) and Faulkner and Marshall (1993) were "absorbed dose in tissue using a dosimeter placed at or near the surface of the body" (NRPB, 1980). This dose quantity can be converted to deep dose equivalent [*i.e.*, $H_p(10)$] by multiplying by a factor of 1.07 (NRPB, 1990). The original dose equivalents have been modified by this factor and converted to $H_p(10)$ in this Report.

Tables 3.4 and 3.5 present the results for the neck and waist film badges when the indicated thicknesses of protective aprons are worn. Usually, the apron thickness is 0.5 mm lead equivalent, but auxiliary staff sometimes use thinner aprons or the back portion of a wrap-around apron may be thinner, such as 0.3 mm lead equivalent.

The conversions between H_E or E and $H_p(10)$ for the film badges worn under the apron at the waist are quite variable with kVp. The fluctuations in kVp used during various fluoroscopy procedures render a direct application of these conversions for individual workers impractical. The conversions between H_E or E and $H_p(10)$ for the film badges worn outside and above the apron at the neck are less variable with kVp, differing by less than a factor of 3 for H_E and less than a factor of 3.4 for E.

TABLE 3.4—*Conversion of $H_p(10)$ for the film badge to H_E, apron present, overtable x-ray tube only (Faulkner and Harrison, 1988).*

	Neck Badge Above Apron (not shielded)		Waist Badge Under Apron (shielded)	
Tube Voltage (kVp)	Apron Thickness (mm lead equivalent)			
	0.3	0.5	0.3	0.5
	To obtain H_E —divide $H_p(10)$ by—		To obtain H_E —multiply $H_p(10)$ by—	
60	25	25	13	56
90	18	20	1.9	5.6
120	8.9	9.7	1.1	2.6

3.3.3 *Results for Effective Dose Equivalent*

$H_p(10)$ for the waist film badge is highly variable with kVp and the equivalent lead thickness of the apron, ranging from 1.1 to 56 times lower than the corresponding H_E. $H_p(10)$ for the neck film badge is less variable, ranging from 8.9 to 25 times higher. The ratio of $H_p(10)$ for the neck film badge to H_E reaches a limiting minimum of 8.9 at 120 kVp with a 0.3 mm lead equivalent apron, when the x-ray tube is in the overtable position. That is, $H_p(10)$ for the neck film badge is higher than H_E by a factor of 8.9 or more, but not higher than about three times that factor for the conditions listed (*i.e.*, not higher than a factor of 25).

In a previous experimental study, Wøhni and Stranden (1979) also investigated the relationships between the film badge response at the neck (located at the right-hand side of the thorax) and H_E for various fluoroscopic conditions, including both over- and undertable x-ray tube orientations. The amount of scatter radiation observed from undertable orientation was less than from overtable orientation, while the distribution of the scatter radiation from undertable orientation was skewed towards the lower body, which can be shielded by protective devices located on the fluoroscopic system (Faulkner and Moores, 1982).

From the Wøhni and Stranden study, the increase in the ratio of H_E to the film badge response for undertable orientation is observed to be fairly constant. For the combination of kVp and equivalent lead thickness of the apron that corresponds to the overtable limiting condition, the increase in this ratio is a factor of 1.6. A revised limiting minimum ratio that includes consideration of both under- and overtable x-ray tube orientations would be 5.6 (*i.e.*, the minimum value for the overtable case of 8.9 divided by 1.6).

Webster (1989) proposed another approach for using the experimental findings for H_E (Faulkner and Harrison, 1988) that removes

TABLE 3.5—*Conversion of $H_p(10)$ for the film badge to E, apron present, over- and undertable x-ray tubes (Faulkner and Marshall, 1993).*

Tube Voltage (kVp)	Neck Badge Over Apron (not shielded)				Waist Badge Under Apron (shielded)			
	Apron Thickness (mm lead equivalent)							
	0.3		0.5		0.3		0.5	
	Over-table	Under-table	Over-table	Under-table	Over-table	Under-table	Over-table	Under-table
	To obtain E divide H_p (10) by				To obtain E multiply $H_p(10)$ by			
70	51	34	57	40	1.8	1.2	6.7	4.5
90	63	27	72	33	1.1	0.9	2.9	2.2
110	21	25	31	35	0.7	0.6	1.4	1.1

the need for specific information regarding kVp and the equivalent lead thickness of the apron. The method requires that monitoring devices be worn both under the apron at the waist and at the neck outside and above the apron. The wearing of both personal monitors is already recommended for medical fluoroscopy (ICRP, 1982; NCRP, 1978c; 1981). Webster developed an empirical formula that uses the results of both monitoring devices to estimate H_E. The formula and the values it would yield relative to the H_E values measured by Faulkner and Harrison (1988) are presented in Table 3.6. This formula is the one incorporated by CRCPD into its current *Suggested State Regulations for the Control of Radiation* (CRCPD, 1995).

H_W and H_N are the values of $H_p(10)$ for the personal monitors worn at the waist and neck, respectively. The formula results in values between 0.97 to 1.07 H_E for 0.5 mm lead equivalent aprons and between 1.12 to 1.72 H_E for 0.3 mm lead equivalent aprons. Use of the formula is a simple and practical way to estimate H_E when both personal monitors are worn.

3.3.4 *Results for Effective Dose*

In Table 3.5, it can be seen that $H_p(10)$ for the waist film badge is quite variable, ranging from 0.6 times higher to 6.7 times lower than the corresponding E. $H_p(10)$ for the neck film badge is less variable, ranging from 21 to 72 times higher. The ratio of $H_p(10)$ for the neck film badge to E reaches a limiting minimum of 21 (*i.e.*, for all over- or undertable cases studied) at 110 kVp and 0.3 mm lead equivalent apron, when the x-ray tube is in the overtable position. That is, $H_p(10)$ for the neck film badge is higher than E by a factor

TABLE 3.6—*Empirical formula and estimates for H_E using two personal monitors and the conversions derived from Faulkner and Harrison (1988), apron present, overtable x-ray tube (Webster, 1989).*

	Estimate of $H_E = 1.5\ H_W + 0.04\ H_N$[a]	
Apron Thickness (mm lead equivalent)	Tube Voltage (kVp)	Estimate of H_E Relative to a Value of 1.0
0.5[b]	60	1.03
	90	1.07
	120	0.97
0.3	60	1.12
	90	1.50
	120	1.72

[a]H_W is the value of $H_p(10)$ for the personal monitor worn under a protective apron at the waist and H_N is the value of $H_p(10)$ for the personal monitor worn outside and above the apron at the neck.

[b]Usual apron thickness.

of 21 or more, but not higher than 3.4 times that factor for the conditions listed (*i.e.*, not higher than a factor of 72).

Using the approach of Webster, with the experimental findings for E (Faulkner and Marshall, 1993), one can produce an empirical formula for E that uses the results of monitoring devices worn under the apron at the waist and at the neck outside and above the apron, comparable to the formula developed for H_E (Rosenstein and Webster, 1994). The formula and the values it yields relative to the E values measured by Faulkner and Marshall (1993) are presented in Table 3.7.

The criteria for a desired formula for E for radiation protection purposes are: (1) minimize the underestimates of E, even at the expense of larger overestimates of E for some conditions, and (2) obtain a close estimate of E at the combination most frequently encountered in clinical practice (*i.e.*, 90 kVp, 0.5 mm lead equivalent apron and undertable x-ray tube) (Rosenstein and Webster, 1994).

The formula results in values between 1.06 and 1.96 E for 0.5 mm lead equivalent aprons and between 1.21 to 2.03 E for 0.3 mm lead equivalent aprons. Use of the formula is a simple and practical way to estimate E when both personal monitors are worn.

TABLE 3.7—*Empirical formula and estimates for E using two personal monitors, derived from Faulkner and Marshall (1993) and Rosenstein and Webster (1994), apron present, over- and undertable x-ray tubes.*

	Estimate of $E = 0.5\ H_W + 0.025\ H_N$[a]	
Apron Thickness (mm lead equivalent)	Tube Voltage (kVp)	Estimate of E Relative to a Value of 1.0
0.5[b] overtable	70	1.49
	90	1.96
	110	1.13
0.5[b] undertable	70	1.10
	90	1.06
	110	1.34
0.3 overtable	70	1.56
	90	2.03
	110	1.26
0.3 undertable	70	1.27
	90	1.21
	110	1.44

[a]H_W is the value of $H_p(10)$ for the personal monitor worn under a protective apron at the waist and H_N is the value of $H_p(10)$ for the personal monitor worn outside and above the apron at the neck.

[b]Usual apron thickness.

4. Recommendations

4.1 Use of Personal Dose Equivalent for a Strongly-Penetrating Radiation Value Determined with One Personal Monitor as a Surrogate for Effective Dose Equivalent

An $H_p(10)$ value determined with one personal monitor is recommended as a surrogate for H_E for working conditions where the locations of the personal monitor, photon energies and irradiation geometries are consistent with those listed below:

- Personal monitor located at the center of the chest (*i.e.*, the front); photon energy greater than 40 keV
  - broad parallel beam from front to back (anterior to posterior)
  - broad parallel beam from either side (lateral)
  - uniform field from all directions (isotropic)
  - uniform field from all directions that are perpendicular to body axis (planar isotropic)
- Personal monitor located at the center of the back (*i.e.*, the back); photon energy greater than 50 keV
  - broad parallel beam from back to front (posterior to anterior)

Under these conditions, $H_p(10)$ would not underestimate the value of H_E except for a slight underestimate for the planar isotropic case in the region of 100 to 200 keV. Also, $H_p(10)$ would not overestimate the value of H_E by more than a factor of two. This meets conservatively safe criteria for radiation protection purposes.

For the most frequently encountered condition of anterior to posterior irradiation with the personal monitor located on the front of the body, $H_p(10)$ would not overestimate the value of H_E by more than a factor of three even down to 30 keV.

4.2 Use of Personal Dose Equivalent for Strongly-Penetrating Radiation Values Determined from Two Personal Monitors to Estimate Effective Dose Equivalent

For working conditions not listed in Section 4.1 or for scenarios where the irradiation geometry or photon energy is unknown or difficult to characterize, the use of $H_p(10)$ values obtained with two personal monitors is recommended, one located on the front of the body (*i.e.*, at the center of the chest) and one located on the back of the body (*i.e.*, at the center of the back).

Evaluation of a number of irradiation scenarios and approaches to combining the $H_p(10)$ values from the two personal monitors indicates that an algorithm developed by the NCRP using the $H_p(10)$ values for the front and back personal monitors of the form:

$$H_E \text{ (estimate)} = 0.55\, H_p(10)_{\text{front}} + 0.50\, H_p(10)_{\text{back}} \qquad (4.1)$$

yields consistent results and generally does not underestimate H_E by more than 10 percent (seldom by more than 5 percent; one exception of 14 percent) and generally does not overestimate H_E by more than factor of two to three (most often less than a factor of two). This meets conservatively safe criteria for radiation protection purposes.

4.3 When a Protective Apron Is Worn During Diagnostic and Interventional Medical Procedures Using Fluoroscopy

When a single personal monitor worn at the neck outside and above a protective apron is used, dividing H_N, [*i.e.*, the $H_p(10)$ value for this personal monitor] by 5.6 to obtain a conservatively high estimate of H_E is recommended. Likewise, dividing H_N by 21 to obtain a conservatively high estimate of E is recommended. These modifications of H_N give appropriate credit for the protection afforded by the apron and do not overestimate the value of H_E by more than a factor of three or the value of E by more than a factor of 3.4.

When two personal monitors are used, one worn under a protective apron at the waist or on the chest [where H_W is the $H_p(10)$ value for this personal monitor] and the other worn outside and above the apron at the neck, it is recommended that the value of H_E be estimated from the formula:

$$H_E \text{ (estimate)} = 1.5\, H_W + 0.04\, H_N. \qquad (4.2)$$

The resulting value of H_E (estimate) will be in the range of 0.97 to 1.72 H_E.

It is recommended that the value of E be estimated from the formula:

$$E \text{ (estimate)} = 0.5\, H_W + 0.025\, H_N. \qquad (4.3)$$

The resulting value of E (estimate) will be in the range of 1.06 to 2.03 E.

If an individual performs both radiographic procedures (*i.e.*, procedures without use of a protective apron) and fluoroscopic procedures (*i.e.*, procedures with the use of a protective apron) during a given monitoring period, there may be no practical way to determine precisely the relative contribution each type of procedure made to the total $H_p(10)$ value recorded by a personal monitor. However, occupational exposure during radiographic procedures should be very low, since the worker is at a relatively large distance from the x-ray source and most often (*i.e.*, except for use of mobile x-ray systems) in a protective cubicle.

If an individual's workload consists predominantly of fluoroscopic procedures, the recommendations given above with the protective apron are appropriate, when either a personal monitor is worn only at the neck outside and above the apron, or when personal monitors are worn both at the neck outside and above the apron and at the waist or chest under the apron. When the $H_p(10)$ values recorded by the personal monitor worn at the waist or chest under the apron are consistently below the minimum detectable values, use of the recommendation for a personal monitor worn only at the neck outside and above the apron would be the more conservatively safe approach.

If an individual's workload consists predominantly of radiographic procedures, where protective aprons are not worn, the recommendation given in Section 4.1 for use of $H_p(10)$ from one personal monitor as a surrogate for H_E would be appropriate. For radiographic procedures, the irradiation conditions are adequately characterized by an anterior to posterior irradiation at effective energies of greater than 30 keV, with a personal monitor located on the front of the individual.

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Currently, the following subgroups are actively engaged in formulating recommendations:

SC 1 Basic Radiation Protection Criteria
- SC 1-4 Extrapolation of Risk from Non-Human Experimental Systems to Man
- SC 1-5 Uncertainty in Risk Estimates
- SC 1-6 Basis for the Linearity Assumption
- SC 1-7 Information Needed to Make Radiation Protection Recommendations for Travel Beyond Low-Earth Orbit

SC 9 Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV

SC 46 Operational Radiation Safety
- SC 46-8 Radiation Protection Design Guidelines for Particle Accelerator Facilities
- SC 46-10 Assessment of Occupational Doses from Internal Emitters
- SC 46-11 Radiation Protection During Special Medical Procedures
- SC 46-13 Design of Facilities for Medical Radiation Therapy

SC 57 Dosimetry and Metabolism of Radionuclides
- SC 57-2 Respiratory Tract Model
- SC 57-9 Lung Cancer Risk
- SC 57-10 Liver Cancer Risk
- SC 57-14 Placental Transfer
- SC 57-15 Uranium
- SC 57-16 Uncertainties in the Application of Metabolic Models

SC 63 Radiation Exposure Control in a Nuclear Emergency

SC 64 Radionuclides in the Environment
- SC 64-17 Uncertainty in Environmental Transport in the Absence of Site Specific Data
- SC 64-18 Risks from Space Applications of Plutonium
- SC 64-19 Historical Dose Evaluation
- SC 64-20 Contaminated Soil
- SC 64-21 Decontamination and Decommissioning of Facilities

SC 66 Biological Effects and Exposure Criteria for Ultrasound

SC 69 Efficacy of Radiographic Procedures

SC 72 Radiation Protection in Mammography

SC 75 Guidance on Radiation Received in Space Activities

SC 77 Guidance on Occupational and Public Exposure Resulting from Diagnostic Nuclear Medicine Procedures

SC 85 Risk of Lung Cancer from Radon

SC 86 Hot Particles in the Eye, Ear or Lung

SC 87 Radioactive and Mixed Waste
- SC 87-1 Waste Avoidance and Volume Reduction
- SC 87-2 Waste Classification Based on Risk
- SC 87-3 Performance Assessment

SC 88 Fluence as the Basis for a Radiation Protection System for Astronauts

SC 89 Nonionizing Electromagnetic Fields
- SC 89-1 Biological Effects of Magnetic Fields
- SC 89-3 Extremely Low-Frequency Electric and Magnetic Fields
- SC 89-4 Modulated Radiofrequency Fields
- SC 89-5 Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields

SC 91 Radiation Protection in Medicine
- SC 91-1 Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides
- SC 91-2 Dentistry

SC 92 Policy Analysis and Decision Making
SC 93 Radiation Measurement

In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and effects, or radiation protection may be admitted to collaborating status by the Council. Collaborating Organizations provide a means by which the NCRP can gain input into its activities from a wider segment of society. At the same time, the relationships with the Collaborating Organizations facilitate wider dissemination of information about the Council's activities, interests and concerns. Collaborating Organizations have the opportunity to comment on draft reports (at the time that these are submitted to the members of the Council). This is intended to capitalize on the fact that Collaborating Organizations are in an excellent position to both contribute to the identification of what needs to be treated in NCRP reports and to identify problems that might result from proposed recommendations. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

American Academy of Dermatology
American Academy of Environmental Engineers
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American Association of Physicists in Medicine
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American College of Occupational and Environmental Medicine
American College of Radiology
American Dental Association
American Industrial Hygiene Association
American Institute of Ultrasound in Medicine
American Insurance Services Group
American Medical Association
American Nuclear Society
American Pharmaceutical Association
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society

American Society of Health-System Pharmacists
American Society of Radiologic Technologists
American Society for Therapeutic Radiology and Oncology
Association of University Radiologists
Bioelectromagnetics Society
Campus Radiation Safety Officers
College of American Pathologists
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Electric Power Research Institute
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United States Coast Guard
United States Department of Energy
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United States Department of Transportation
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Services
Utility Workers Union of America

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of the NCRP relates to the Special Liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and the NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the Special Liaison Program:

Australian Radiation Laboratory
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Commission of the European Communities
Defense Nuclear Agency
Health Council of the Netherlands
International Commission on Non-Ionizing Radiation Protection
Japan Radiation Council
Korea Institute of Nuclear Safety
National Radiological Protection Board (United Kingdom)
National Research Council (Canada)
Office of Science and Technology Policy
South African Forum for Radiation Protection
Ultrasonics Institute (Australia)
United States Air Force
United States Nuclear Regulatory Commission

The NCRP values highly the participation of these organizations in the Special Liaison Program.

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American Medical Association
American Nuclear Society
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Initial funds for publication of NCRP reports were provided by a grant from the James Picker Foundation.

The NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

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NCRP Reports

No.	Title
8	*Control and Removal of Radioactive Contamination in Laboratories* (1951)
22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
32	*Radiation Protection in Educational Institutions* (1966)
35	*Dental X-Ray Protection* (1970)
36	*Radiation Protection in Veterinary Medicine* (1970)
37	*Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides* (1970)
38	*Protection Against Neutron Radiation* (1971)
40	*Protection Against Radiation from Brachytherapy Sources* (1972)
41	*Specification of Gamma-Ray Brachytherapy Sources* (1974)
42	*Radiological Factors Affecting Decision-Making in a Nuclear Attack* (1974)

101 *Exposure of the U.S. Population from Occupational Radiation* (1989)
102 *Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use)* (1989)
103 *Control of Radon in Houses* (1989)
104 *The Relative Biological Effectiveness of Radiations of Different Quality* (1990)
105 *Radiation Protection for Medical and Allied Health Personnel* (1989)
106 *Limit for Exposure to "Hot Particles" on the Skin* (1989)
107 *Implementation of the Principle of As Low As Reasonably Achievable (ALARA) for Medical and Dental Personnel* (1990)
108 *Conceptual Basis for Calculations of Absorbed-Dose Distributions* (1991)
109 *Effects of Ionizing Radiation on Aquatic Organisms* (1991)
110 *Some Aspects of Strontium Radiobiology* (1991)
111 *Developing Radiation Emergency Plans for Academic, Medical or Industrial Facilities* (1991)
112 *Calibration of Survey Instruments Used in Radiation Protection for the Assessment of Ionizing Radiation Fields and Radioactive Surface Contamination* (1991)
113 *Exposure Criteria for Medical Diagnostic Ultrasound: I. Criteria Based on Thermal Mechanisms* (1992)
114 *Maintaining Radiation Protection Records* (1992)
115 *Risk Estimates for Radiation Protection* (1993)
116 *Limitation of Exposure to Ionizing Radiation* (1993)
117 *Research Needs for Radiation Protection* (1993)
118 *Radiation Protection in the Mineral Extraction Industry* (1993)
119 *A Practical Guide to the Determination of Human Exposure to Radiofrequency Fields* (1993)
120 *Dose Control at Nuclear Power Plants* (1994)
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122 *Use of Personal Monitors to Estimate Effective Dose Equivalent and Effective Dose to Workers for External Exposure to Low-LET Radiation* (1995)

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(Titles of the individual reports contained in each volume are given above.)

NCRP Commentaries

No.	Title
1	*Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)
3	*Screening Techniques for Determining Compliance with Environmental Standards—Releases of Radionuclides to the Atmosphere* (1986), Revised (1989)

4	*Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)
5	*Review of the Publication, Living Without Landfills* (1989)
6	*Radon Exposure of the U.S. Population—Status of the Problem* (1991)
7	*Misadministration of Radioactive Material in Medicine—Scientific Background* (1991)
8	*Uncertainty in NCRP Screening Models Relating to Atmospheric Transport, Deposition and Uptake by Humans* (1993)
9	*Considerations Regarding the Unintended Radiation Exposure of the Embryo, Fetus or Nursing Child* (1994)
10	*Advising the Public about Radiation Emergencies: A Document for Public Comment* (1994)
11	*Dose Limits for Individuals Who Receive Exposure from Radionuclide Therapy Patients* (1995)
12	*Radiation Exposure and High-Altitude Flight* (1995)
13	*An Introduction to Efficacy in Diagnostic Radiology and Nuclear Medicine (Justification of Medical Radiation Exposure)* (1995)

Proceedings of the Annual Meeting

No.	Title
1	*Perceptions of Risk,* Proceedings of the Fifteenth Annual Meeting held on March 14-15, 1979 (including Taylor Lecture No. 3) (1980)
3	*Critical Issues in Setting Radiation Dose Limits,* Proceedings of the Seventeenth Annual Meeting held on April 8-9, 1981 (including Taylor Lecture No. 5) (1982)
4	*Radiation Protection and New Medical Diagnostic Approaches,* Proceedings of the Eighteenth Annual Meeting held on April 6-7, 1982 (including Taylor Lecture No. 6) (1983)
5	*Environmental Radioactivity,* Proceedings of the Nineteenth Annual Meeting held on April 6-7, 1983 (including Taylor Lecture No. 7) (1983)
6	*Some Issues Important in Developing Basic Radiation Protection Recommendations,* Proceedings of the Twentieth Annual Meeting held on April 4-5, 1984 (including Taylor Lecture No. 8) (1985)

7 *Radioactive Waste,* Proceedings of the Twenty-first Annual Meeting held on April 3-4, 1985 (including Taylor Lecture No. 9) (1986)

8 *Nonionizing Electromagnetic Radiations and Ultrasound,* Proceedings of the Twenty-second Annual Meeting held on April 2-3, 1986 (including Taylor Lecture No. 10) (1988)

9 *New Dosimetry at Hiroshima and Nagasaki and Its Implications for Risk Estimates,* Proceedings of the Twenty-third Annual Meeting held on April 8-9, 1987 (including Taylor Lecture No. 11) (1988)

10 *Radon,* Proceedings of the Twenty-fourth Annual Meeting held on March 30-31, 1988 (including Taylor Lecture No. 12) (1989)

11 *Radiation Protection Today—The NCRP at Sixty Years,* Proceedings of the Twenty-fifth Annual Meeting held on April 5-6, 1989 (including Taylor Lecture No. 13) (1990)

12 *Health and Ecological Implications of Radioactively Contaminated Environments,* Proceedings of the Twenty-sixth Annual Meeting held on April 4-5, 1990 (including Taylor Lecture No. 14) (1991)

13 *Genes, Cancer and Radiation Protection,* Proceedings of the Twenty-seventh Annual Meeting held on April 3-4, 1991 (including Taylor Lecture No. 15) (1992)

14 *Radiation Protection in Medicine,* Proceedings of the Twenty-eighth Annual Meeting held on April 1-2, 1992 (including Taylor Lecture No. 16) (1993)

15 *Radiation Science and Societal Decision Making,* Proceedings of the Twenty-ninth Annual Meeting held on April 7-8, 1993 (including Taylor Lecture No. 17) (1994)

Lauriston S. Taylor Lectures

No.	Title
1	*The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977)
2	*Why be Quantitative about Radiation Risk Estimates?* by Sir Edward Pochin (1978)
3	*Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk,* see above]
4	*From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980)

5 *How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits,* see above]

6 *Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches,* see above]

7 *The Human Environment—Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity,* see above]

8 *Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations,* see above]

9 *Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste,* see above]

10 *Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions* by Herman P. Schwan (1987) [Available also in *Nonionizing Electromagnetic Radiations and Ultrasound,* see above]

11 *How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1988) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates,* see above]

12 *How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon,* see above]

13 *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today,* see above]

14 *Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990) [Available also in *Health and Ecological Implications of Radioactively Contaminated Environments,* see above]

15 *When is a Dose Not a Dose?* by Victor P. Bond (1992) [Available also in *Genes, Cancer and Radiation Protection,* see above]

16 *Dose and Risk in Diagnostic Radiology: How Big? How Little?* by Edward W. Webster (1992)[Available also in *Radiation Protection in Medicine,* see above]

17 *Science, Radiation Protection and the NCRP* by Warren K. Sinclair (1993)[Available also in *Radiation Science and Societal Decision Making,* see above]

18 *Mice, Myths and Men* by R.J. Michael Fry (1995)

Symposium Proceedings

No.	Title
1	*The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack,* Proceedings of a Symposium held April 27-29, 1981 (1982)
2	*Radioactive and Mixed Waste—Risk as a Basis for Waste Classification,* Proceedings of a Symposium held November 9, 1994 (1995)

NCRP Statements

No.	Title
1	"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology 63, 428 (1954)
2	"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. 84, 152 (1960) and Radiology 75, 122 (1960)
3	*X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements* (1968)
4	*Specification of Units of Natural Uranium and Natural Thorium, Statement of the National Council on Radiation Protection and Measurements* (1973)
5	*NCRP Statement on Dose Limit for Neutrons* (1980)
6	*Control of Air Emissions of Radionuclides* (1984)
7	*The Probability That a Particular Malignancy May Have Been Caused by a Specified Irradiation* (1992)

Other Documents

The following documents of the NCRP were published outside of the NCRP report, commentary and statement series:

Somatic Radiation Dose for the General Population, Report of the Ad Hoc Committee of the National Council on Radiation Protection and Measurements, 6 May 1959, Science, February 19, 1960, Vol. 131, No. 3399, pages 482-486

Dose Effect Modifying Factors in Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service Springfield, Virginia)

The following documents are now superseded and/or out of print:

NCRP Reports

No.	Title
1	*X-Ray Protection* (1931) [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934) [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936) [Superseded by NCRP Report No. 6]
4	*Radium Protection* (1938) [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compound* (1941) [Out of Print]
6	*Medical X-Ray Protection Up to Two Million Volts* (1949) [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949) [Superseded by NCRP Report No. 30]
9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951) [Out of Print]
10	*Radiological Monitoring Methods and Instruments* (1952) [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953) [Superseded by NCRP Report No. 22]
12	*Recommendations for the Disposal of Carbon-14 Wastes* (1953) [Superseded by NCRP Report No. 81]
13	*Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954) [Superseded by NCRP Report No. 24]
14	*Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts* (1954) [Superseded by NCRP Report No. 51]
15	*Safe Handling of Cadavers Containing Radioactive Isotopes* (1953) [Superseded by NCRP Report No. 21]
16	*Radioactive-Waste Disposal in the Ocean* (1954) [Out of Print]

17 *Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposures to Man, Addendum to National Bureau of Standards Handbook 59* (1958) [Superseded by NCRP Report No. 39]

18 *X-Ray Protection* (1955) [Superseded by NCRP Report No. 26]

19 *Regulation of Radiation Exposure by Legislative Means* (1955) [Out of Print]

20 *Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957) [Superseded by NCRP Report No. 38]

21 *Safe Handling of Bodies Containing Radioactive Isotopes* (1958) [Superseded by NCRP Report No. 37]

24 *Protection Against Radiations from Sealed Gamma Sources* (1960) [Superseded by NCRP Reports No. 33, 34 and 40]

26 *Medical X-Ray Protection Up to Three Million Volts* (1961) [Superseded by NCRP Reports No. 33, 34, 35 and 36]

28 *A Manual of Radioactivity Procedures* (1961) [Superseded by NCRP Report No. 58]

29 *Exposure to Radiation in an Emergency* (1962) [Superseded by NCRP Report No. 42]

31 *Shielding for High-Energy Electron Accelerator Installations* (1964) [Superseded by NCRP Report No. 51]

33 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Equipment Design and Use* (1968) [Superseded by NCRP Report No. 102]

34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation Handbook* (1970) [Superseded by NCRP Report No. 49]

39 *Basic Radiation Protection Criteria* (1971) [Superseded by NCRP Report No. 91]

43 *Review of the Current State of Radiation Protection Philosophy* (1975) [Superseded by NCRP Report No. 91]

45 *Natural Background Radiation in the United States* (1975) [Superseded by NCRP Report No. 94]

48 *Radiation Protection for Medical and Allied Health Personnel* (1976) [Superseded by NCRP Report No. 105]

53 *Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally-Exposed Women* (1977) [Out of Print]

56 *Radiation Exposure from Consumer Products and Miscellaneous Sources* (1977) [Superseded by NCRP Report No. 95]

58 *A Handbook of Radioactivity Measurements Procedures, 1st ed.* (1978) [Superseded by NCRP Report No. 58, 2nd ed.]

66 *Mammography* (1980) [Out of Print]

91 *Recommendations on Limits for Exposure to Ionizing Radiation* (1987) [Superseded by NCRP Report No. 116]

NCRP Commentaries

No.	Title
2	*Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982) [Out of Print]

NCRP Proceedings

No.	Title
2	*Quantitative Risk in Standards Setting,* Proceedings of the Sixteenth Annual Meeting held on April 2-3, 1980 [Out of Print]

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