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Citation: Medical Physics 13, 913 (1986); doi: 10.1118/1.595817
View online: http://dx.doi.org/10.1118/1.595817
View Table of Contents: http://scitation.aip.org/content/aapm/journal/medphys/13/6?ver=pdfcov
Published by the American Association of Physicists in Medicine
Exposure and organ dose estimation in diagnostic radiology

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(Received 2 April 1986; accepted for publication 12 August 1986)

This paper discusses a methodology which uses a specially developed computer program that enables estimation of output parameters of an x-ray machine from a single test exposure. Exposure at skin entrance values can be estimated, as well as using the data from the program for organ dose estimates. To perform the estimation procedure, curves and analytical expressions for the curves are presented for conversion of half-value layers to total filtration and for conventional mR/mAs output curves. Results are given showing that the estimation procedure is reasonably accurate.

Key words: radiations, exposure to patients, dosimetry, diagnostic radiology, radiation dose, computers

INTRODUCTION

There has been recent interest in the development of guidelines for skin exposures (free-in-air) to patients undergoing examinations in diagnostic radiology. In federal facilities, as well as in several states, guidelines and regulations have been published which give exposure at skin entrance (ESE) values for several common diagnostic x-ray procedures. The federal guidance values reflect the third quartile values obtained from the National Evaluation of X-Ray Trends (NEXT) program. These guidelines may also be useful in directing the responsible person’s attention to procedures that may bear closer scrutiny in the case of apparent high ESE. Another useful function of ESE values is that they may be applied in computing organ doses by standard methodology.

One procedure for determining ESE’s is to physically measure the x-ray machine output for each examination technique used. However, this is normally impractical during a routine x-ray machine survey, and generally only one technique is checked for output. Then if one knows variability in output as a function of kVp and filtration, the exposure and half-value layer (HVL) for any set of technique factors can be calculated using the single test exposure.

METHODS

Estimation of exposures for other technique factors from a single test exposure technique may be represented by the expression

\[ mR_o = mR_e \times CF(\text{filir}, \frac{kVp}{kVp_o}, \frac{mAs}{mAs_o}, \frac{\text{dist}_o}{\text{dist}})^2, \]  

where \( kVp, mAs, mR, \text{HVL}, \text{and dist} \) = parameters used and acquired in test exposure; \( mR_o = \) estimated exposure at other parameters \( kVp_o, mAs_o, \text{and dist}_o \) (\( mR_o \) can be considered to be ESE if the other parameters are properly input for this purpose); \( CF(\text{filir}, kVp/kVp_o) \) = correction factor (CF) giving the relative output in mR/mAs at \( kVp_o \) and \( kVp \), at the filtration of the machine; and \( \text{filir} = f(kVp, \text{HVL}) \), i.e., the filtration of the machine is found by the functional relationship of the \( kVp \) and \( \text{HVL} \).

Computation of Eq. (1) is straightforward except for determination of the parameter \( CF(\text{filir}, kVp/kVp_o) \). Finding this parameter and hence ESE for other techniques from a single test exposure involves a two-step process with each step possibly involving a two-way interpolation of data between curves. This is somewhat complex and tedious if done by hand; briefly, the basic procedure is to: (a) find the estimated total filtration of the system by referring to curves giving the total filtration as a function of HVL and \( kVp \), and (b) once the filtration is found, a second family of curves gives the relation between relative output (mR/mAs) as a function of kVp and filtration.

There is a paucity of data in the literature to enable step (a) to be performed, especially at the higher filtrations commonly used at present. Curves giving HVL versus filtration as a function of kVp for three-phase generators were developed to enable this to be done based on interpolation and extrapolation of data in Refs. 9–11. The curve development process was to fit the 70- and 100-kVp data with a second-order polynomial by the method of least squares. The 70- and 100-kVp curves were chosen because of the relatively large amount of HVL/filtration data published for these.
kVp's and because the filtrations used ranged from 1.5 to 5 mm Al, which was the range considered for the purposes of this paper. Using Refs. 9–11 is somewhat of a compromise approach, since there is no consensus on the actual relationship between HVL and filtration. In practice, the relationship is actually machine specific rather than the assumption made, which is that there is a single, general relationship. Smooth curves were hand drawn for the remainder of the kVp's, based on the general shape of the 70- and 100-kVp curves. The least-squares fitting process was not appropriate for the other kVp's because of the sparse amount and limited filtration range of the data.

The data for single-phase generators was based on data in Refs. 10, 12, and 13, and curves were developed in the same manner as that described for the three-phase data.

After the curves were drawn, second-order polynomials were found for the curves to facilitate computer computations. Similarly, second-order polynomials were fitted to the relative output data (mR/mAs as a function of HVL and kVp) for computer calculations.

After the above-described analytical expressions for the curves were found, we wrote a computer program in BASIC that obviates the tedium of performing the computations and interpolations by hand (a copy of the program is available from the authors upon request). A linear interpolation is done by the computer to generate values between the curves. The program asks for input of test parameters acquired during the machine survey: kVp, mAs, distance, mR, and generator phase. The program can then output ESE values based on further input of the normal technique used for these exams. For organ dosimetry, the program can output data for any other specified exam or can generate a table of relative output (mR/mAs) for various kVp's. The corresponding HVL is also printed, since this is required for organ dosimetry. The HVL at kVp's other than the test exposure kVp is found from a relationship using the same data as that used to generate the previously described curves.

To check the accuracy of the estimation procedure, output data for various x-ray machines were acquired locally at two facilities and, in addition, previously published data were used.14–16 The data include single-phase and three-phase generators. Local data were acquired using an MDH model 1015 system (Radcalc Corp., Monrovia, CA), an RMI electronic kVp cassette (Radiation Measurements, Inc., Middleton, WI), and a Victoreen NERO system (Cleveland, OH). Exposure accuracy for the MDH system is given as ±3%, with an energy dependence of ±5%. For the NERO system, exposure accuracy is given as ±10%, and the kVp accuracy is given as ±3 kVp or ±3%, whichever is greater. For the RMI meter, the kVp accuracy is given as ±2%. All instruments had been calibrated within the previous year, with the calibration traceable to NBS.

The parameters of interest (mR and HVL), estimated using the methodology of this paper, are compared against the actual parameters found for the particular x-ray machine. The single technique used to estimate the parameters for the other techniques was usually chosen to be the 80-kVp exposure or the kVp nearest the 80-kVp exposure. In addition, HVL data were obtained for two three-phase machines at approximately 60-, 80-, 100-, and 120-kVp stations with the inherent filtrations of each unit adjusted to yield a variety of HVL's. HVL data were also supplied in Refs. 13–15. For the organ dose estimates, a lateral thoracic spine exposure was assumed, and the dose to the active bone marrow and thyroid was computed, based on the actual (measured) output and HVL and the estimated output and HVL. Organ dose data (rad/R as a function of HVL) from Ref. 7 were used, except for the procedures in which the HVL was greater than 4.0 mm Al. In these instances, data in Ref. 17 were used.

RESULTS

Figures 1 and 2 present the curves giving the relationship between filtration, HVL, and kVp for three-phase and single-phase generators. As stated previously, results of McCullough and Cameron9 were used for the mR/mAs
Table I. Coefficients for the family of curves, \( y = a + bx + cx^2 \), given in Figs. 1 and 2 and for mR/mAs data in Ref. 8.

<table>
<thead>
<tr>
<th>kVp</th>
<th>Figure 1</th>
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<th>Figure 2</th>
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<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
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The accuracy of the estimate is defined by

\[ A = \frac{(O - E)}{E} \]

where \( A \) = accuracy, \( O \) = observed (actual) value, and \( E \) = estimate. The overall accuracy of the procedure was then found by determining the mean of the individual \( A \) values (\( A_m \)) and the standard deviation (SD), and was expressed as \( A_m \pm SD \). Using the data shown in Fig. 3, the mR accuracy was found to be 0.04 ± 0.15; the HVL accuracy was -0.04 ± 0.05.

Figure 4 presents the active bone marrow dose accuracy results. Essentially the same accuracy was found for the thyroid dose as for the active bone marrow dose, evidently because the slope of the organ dose curves as a function of the HVL is approximately the same. The overall accuracy of the dose estimates was computed to be -0.01 ± 0.14.

A sample of the output from the computer program is given in Fig. 5, showing the mR and HVL estimates. The input (test) parameters are given at the bottom of the program output.

**DISCUSSION**

It may be seen that the HVL and mR output of a particular diagnostic x-ray unit may be estimated with a reasonable accuracy through a range of technique factors from a single test exposure using the methodology of this paper. The assumptions upon which this estimation procedure relies include mR/mAs generator linearity and accuracy of the filtration data in Figs. 1 and 2 as a function of kVp and HVL.

Various methods have been proposed for estimating exposure and dose in diagnostic radiology. Glaze et al. describe a method using a single test exposure for fetal dosimetry. However, their method assumes that the machine HVL is 3.0 mm Al, which may vary considerably from the actual HVL. Wilson and Palmer have given an empirical method for estimating exposure (mR/mAs) as a function of kVp, filtration, and generator phase. They used the output spectra computed by three previous methods for comparison. They showed that their actual output measured from a variety of diagnostic units compared best with Storm. How-

Fig. 3. Estimation accuracy of methodology described in text for output (mR) and HVL. Accuracy = (actual – est.)/est.

Fig. 4. Estimation accuracy of methodology described for bone marrow dose using output (mR) and HVL estimates computed by methodology described in text. Accuracy = (actual – est.)/est.
In summary, the proposed methodology provides a way for estimating ESE's for a range of technique factors extrapolated from a single test exposure from a diagnostic x-ray machine. Since the HVL is also estimated, the method is valuable in aiding organ dosimetry to be accomplished. The method is applicable to fluoroscopic procedures as well as radiographic ones.

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