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Supplementary Information

Fluoroscopy X-ray Organ-Specific Dosimetry System (FLUXOR) for Estimation of Organ Doses and Their Uncertainties in the Canadian Fluoroscopy Cohort Study

APPENDIX A – FLUXOR Parameter Values and Their Uncertainty

This Appendix provides details on parameters used to estimate organ doses from fluoroscopy examinations related to pneumothorax, pneumoperitoneum and chest aspirations. Probability distributions developed for these parameters represent the uncertainty in the true but unknown average value for each parameter, applicable to specific subgroups within the cohort. Estimated average values of parameters used to calculate doses and their uncertainties from chest radiography and GI series fluoroscopic examinations are discussed elsewhere (1-3).

Parameters in Fluoroscopy Exams Related to Lung-Collapse Therapy

A total of 91 physicians completed a detailed questionnaire given by a trained interviewer during the 1970s. Data reported by physicians in Nova Scotia (23 physicians) and in other provinces (68 physicians) were analyzed separately. Differences between these two regions were observed only in a few parameter values reported by physicians. No significant differences in treatment protocols among other provinces were identified. About 90% of all patients were treated at least once in provinces other than Nova Scotia. Analyses of data on parameters from physician interviews summarized below were carried out by weighting reported values by the number of years of experience for each physician. This approach is based on an assumption that physicians with more years of experience were likely to have more accurate recall of typical exposure conditions and details of different procedures than physicians with fewer years of experience. The percentages of physicians by number of years of experience are as follows: <1 y (5.5%), 1 to 5 y (47.2%), 5 to 10 y (24.2%), 11 to 15 y (14.3%), 16 to 20 y (3.3%), and 21 to 25 y (5.5%).

Tube voltage. A total of 24 physicians (3 in Nova Scotia and 21 in other provinces) provided data on the tube voltage most commonly used in fluoroscopy. Given the few physicians from Nova Scotia, the reported values from all physicians were combined and analyzed together. Tube voltages were reported to be between 50 and 100 kV. By weighting each reported tube voltage by the years of experience of each physician (ranging 2 to 21 y), an average tube voltage of 78 kV was obtained, with a standard deviation of the weighted average of 3.8 kV.

Data in scientific publications and medical textbooks from the period of interest are consistent with tube voltages reported by the physicians. Rigler (1946) (*4*) recommended that tube voltage in general chest fluoroscopy not exceed 90 kV. Tube voltages in chest fluoroscopy of 55 to 90 kV and 70 to 84 kV were reported by Deutschberger (1955) and Bell (1943) (*5, 6*), respectively. Braestrup (1942) and Chamberlain (1942) (*7, 8*) used fluoroscopes from different manufacturers to carry out radiation measurements under conditions typical of medical procedures, and reported tube voltages of 66 to 95 kV and 60 to 100 kV, respectively. In a study of doses received by practicing radiologists in the late 1960s to early 1970s, Jankowski (1972) (*9*) recorded tube voltages of 65 to 75 kV. In an analysis of doses to tuberculosis patients treated in Massachusetts between 1930 and 1954, Boice et al. (1978) (*10*) reported a typical voltage of 75 kV.

In this analysis, the uncertainty in the true but unknown average tube voltage for pneumothorax procedures in adults was assumed to be described by a normal (i.e., Gaussian) probability distribution with a mean of 78 kV and standard deviation of 4.0 kV based on the physician data described above. It is expected that similar machine parameters were used in pneumothorax, chest aspirations, and pneumoperitoneum because (1) the same fluoroscopes were used in all these procedures, and (2) the same organ (lung) was viewed under the same

orientation of the patient (AP or PA). However, since responses from physician interviews referred to pneumothorax procedures only, larger uncertainties were assumed for pneumoperitoneum and chest aspirations. A standard deviation of 5.0 kV was selected to represent the uncertainty in average tube voltages for pneumoperitoneum and chest aspirations.

The assumptions described above apply to exposures of adults. To produce images of similar quality in fluoroscopic exams in children, technical parameters presumably were adjusted to account for the smaller chest thicknesses in children. Information from the literature [e.g., (*5, 11-14*)] suggests that the usual approach to obtaining images of similar quality in fluoroscopy was to reduce the tube voltage for younger ages. Such reductions in tube voltage would compensate for reductions in image contrast with decreasing chest thickness at the same tube voltage. In the period of interest, tube voltages were adjusted manually in steps of ~5 kV using control knobs. In this analysis, it is assumed that tube voltages in fluoroscopic exams were 5 kV lower at ages 10 to 19 y and 10 kV lower at ages 1 to 9 y than in adults; i.e., average tube voltages of 73 kV and 68 kV, respectively, were assumed. Similar adjustments of voltage with age were used in estimating organ doses from chest radiography and GI series fluoroscopic exams (*1, 2).*

The same probability distributions used to describe uncertainties in the average voltage at different ages are assumed to apply to both sexes and to fluoroscopic exams in Nova Scotia and other provinces. In Monte Carlo sampling from those distributions, uncertain average tube voltages at different ages are assumed to be fully correlated, so that the average tube voltage in exposures of children is always smaller than in adults. However, those distributions are sampled independently for fluoroscopic exams in the two regions, and probability distributions for different medical procedures also are sampled independently. This approach accounts for the fact

that the average tube voltage in Nova Scotia could have been different from the average tube voltage in the other provinces and the average tube voltage could have been different for different medical procedures.

Tube current. A total of 43 physicians (11 in Nova Scotia and 32 in other provinces) provided information on the tube current (mA) most commonly used in fluoroscopy. Most reported tube currents ranged from 3 to 6 mA in Nova Scotia and from 2 to 10 mA in other provinces. Two outliers[1] reported by physicians from other provinces were excluded from the analysis. The average tube current, weighted by the years of experience for each physician, was 4.0 mA in Nova Scotia and 4.2 mA in other provinces. Standard deviations of the weighted mean were 0.36 mA in Nova Scotia and 0.37 mA in other provinces.

Mackenzie (1965) (*15*) indicated that physicians in Nova Scotia were strongly advised to use a tube current less than 5 mA, but the use of higher currents apparently was not uncommon when the examiner was busy and did not take time to accommodate his vision. Boice et al. (1978) (*10*) reported that a tube current of 5 mA was consistent with pneumo-therapy practices in Massachusetts from 1930 to 1954. More generally, Rigler (1946) (*4*) recommended a maximum tube current in chest fluoroscopy of 4 mA. Braestrup (1942) (*7*) used fluoroscopes from different manufacturers to carry out radiation measurements under conditions typical of medical procedures and reported a typical tube current of 5 mA. In similar studies, Chamberlain (1942) (*8*) used tube currents of 4 to 8 mA and reported on case studies where physicians used tube currents of 4 to 5 mA. Jankowski (1972) (*9*) reported tube currents of 1.6 to 3.0 mA for chest fluoroscopy in the late 1960s to early 1970s.

[1] Two physicians reported tube currents of 30 and 35 mA. These values presumably were not possible in the period of interest, since the current was limited by the circuitry of the fluoroscope to 15 mA (*5*). Some fluoroscopes could have been limited to 20 or 25 mA, but probably not 30 mA or higher.

In this analysis, uncertain average tube currents in pneumothorax procedures at all ages are assumed to be described by a normal distribution with mean and standard deviation of 4.0 and 0.40 mA, respectively, both in Nova Scotia and in other provinces. As in the analysis of tube voltages, larger uncertainties described by a standard deviation of 0.50 mA are assumed for pneumoperitoneum and chest aspirations in all regions. Those distributions are also sampled independently between the two regions and between medical procedures but are applied fully correlated to both sexes and at all ages at exposure.

Total filtration. Total filtration of an x-ray beam is the sum of the inherent filtration provided by any permanent tube enclosure and any added filtration provided by materials placed in the path of the beam to preferentially absorb less penetrating lower-energy photons. Since physician interviews did not provide information on filtration used during fluoroscopic exams, data on this parameter were obtained from reports on past studies of tuberculosis patients and general scientific literature.

The inherent filtration in historical vertical fluoroscopes used in tuberculosis sanatoria was about 0.5 mm Al (11, 14, 16). In general, fluoroscopes were operated without added filtration until the mid-1940s, after which an added filter of 1 mm Al (total filtration of 1.5 mm Al) was commonly used (*10, 15, 17-19*).

A total filtration in fluoroscopes of up to 1 mm Al was first recommended in the U.S. in National Bureau of Standards (NBS) Handbook 20 (*20*). Braestrup (1942) (*7*) reported total filtrations between 0.5 mm Al and 1 mm Al in fluoroscopes typically used in New York hospitals. NBS recommended the use of a total filtration up to 2 mm Al in Handbook 41 (*21*) and 2.5 mm Al in Handbook 60 (*22*). However, descriptions of medical practices in tuberculosis

sanatoria in Canada (*15, 18*) and the U.S. (*10*) indicate that fluoroscopes in sanatoria were commonly operated with a total filtration of about 1.5 mm Al beginning in the mid-1940s. Mackenzie (1965) (*15*) indicated that fluoroscopic equipment and pneumothorax techniques in treatment of tuberculosis patients in Canada were not further developed from the early 1950s until 1970 when fluoroscopy was no longer used routinely, so it is reasonable to assume that use of 1 mm Al added filtration continued through the 1950s and 1960s, consistent with practices in the U.S. sanatoria (*10*).

Previous dose calculations for CFCS patients (*19*) assumed that fluoroscopes were operated with no added filter before 1948 and 1 mm Al added filtration after 1948. However, to account for uncertainty, it is assumed in this analysis that this change could have occurred in any year during a 10-year period from 1942 through 1951 with equal probability. Thus, in the period 1930 to 1941, the total filtration is assumed to be 0.5 mm Al (i.e., no added filtration), while in the years 1952 to 1969, the total filtration is assumed to be 1.5 mm Al. In the intermediate period of 1942 to 1951, the probability that a 1 mm Al added filter (total filtration of 1.5 mm Al) was used was assumed to increase by 0.1 per year starting from zero up to 1.0 in 1951. During the Monte-Carlo sampling process, doses in that period are allowed to range from doses obtained by assuming no added filtration to doses obtained by assuming 1 mm Al added filter (1.5 mm Al total filter). For example, in 1948, weights of 0.7 and 0.3 are assigned to doses obtained assuming total filtrations of 1.5 and 0.5 mm Al, respectively.

Tube output. Tube output from an x-ray machine is the exposure (R) in air per mA per second at a given tube voltage and total filtration. An exposure rate ($R\ s^{-1}$) is the product of the tube output [$R\ (mA\ s)^{-1}$] and tube current (mA). In estimating organ doses to patients, tube outputs of interest are values at skin entrance with no patient present.

Interviews with physicians about medical practices in sanatoria in Canada did not include questions about the tube output. In this analysis, tube outputs were estimated based on measurements of exposure rates at the fluoroscope panel carried out on vertical fluoroscopes typical of those used in tuberculosis sanatoria in the period 1922 to 1935 [General Electric Victor Vertical Fluoroscope (1922), Fisher Vertical Fluoroscope, Type X (1925), Picker Vertical Fluoroscope, Style T-10 (1935); (*10*)]. As shown in Figure A1, measured fluoroscope outputs increased linearly with increasing tube voltage. At a typical tube voltage of 75 kV and tube current of 4.5 mA, the exposure rate in air would be 0.77 R s^{-1} with no added filter and 0.36 R s^{-1} with 1 mm Al added filtration. These exposure rates correspond to absorbed dose rates in air[2] of 0.0067 and 0.0032 Gy s^{-1}, respectively (*23*).

Three sources of uncertainty in the average tube output are accounted for in estimating organ doses. *First*, uncertainties in point values reported by Boice et al. (1978) (*10*) and shown in Fig. A.1 are estimated by accounting for the assumed uncertainties in tube voltage and total filtration described previously.

A second source of uncertainty arises from an observed variability in tube outputs from different machines at the same tube voltage and total filtration. Tube outputs from historical fluoroscopes reported by Boice et al. (1978) (*10*) were compared with average tube outputs measured in hundreds of radiography machines in the U.S. in the late 1960s (*24*). Differences between tube outputs in these two sets of machines varied from −15% to +20% at tube voltages and total filtrations of interest. Based on measurements on 14 machines that used added filtration, Ritter et al. (1952) (*25*) reported that variations in measured tube outputs at the same tube voltage and filtration were as great as ±20% of average values. Data reported by Martin

[2] Using a conversion factor of 0.00877 Gy R^{-1} (*23*).

(1947) (*26*) and discussed by Ritter et al. (1952) (*25*) indicate that the variability in tube output in machines with no added filtration is expected to be about twice the variability in machines with added filtration. Based on this information, it is assumed in this analysis that the tube output during the time period when fluoroscopes were operated with no added filtration has an uncertainty defined by a multiplicative factor in the form of a normal distribution centered on 1.0 with a 90% CI of (0.6, 1.4); the standard deviation of this distribution is 0.24. At times when fluoroscopes were operated with added filtration, this uncertainty in tube output is described by a multiplicative normal distribution centered on 1.0 with a 90% CI of (0.8, 1.2); the standard deviation of this distribution is 0.12. These distributions are assumed to be fully correlated across all patients and all medical procedures.

A third source of uncertainty in tube output is an uncertainty in the distance from the tube anode to the fluoroscope panel, where the patient was located (Figure 2). Tube outputs reported by Boice et al. (1978) (*10*) were measured at a tube-to-panel distance, d_{meas}, that was not specified precisely but was between 30.5 and 33 cm. In fluoroscopes used in sanatoria in Canada, the average tube-to-panel distance, d_{fluor}, was reported to be about 32.5 cm (*15*), similar to fluoroscopes typically used in all tuberculosis sanatoria during the time period of interest (*5, 10).* However, this distance is uncertain and could have varied from about 30.5 to 33 cm as well. Given these uncertainties, tube outputs used in this analysis (Fig. A.1) are adjusted to account for the possibility that the average tube-to-panel distance d_{fluor} in exposures of CFCS patients could have been longer or shorter than the reported value and different from the tube-to-panel distance, d_{meas}, at which measurements reported by Boice et al. (1978) (*10*) were made. Since tube output varies inversely with the square of the distance from the source, measured tube outputs are adjusted by a multiplicative factor given by $(d_{meas}/d_{fluor})^2$. By describing the uncertainty in d_{meas}

and d_{fluor} by uniform probability distributions between 30.5 and 33 cm, the multiplicative factor to adjust tube output can be represented by a symmetrical triangular probability distribution with a minimum, mode, maximum of 0.85, 1.0, 1.15, respectively. This distribution has a mean and 95% CI of 1.0 (0.88, 1.12). This distribution was applied to all machines with or without added filtration and was assumed to be fully correlated across all medical procedures using fluoroscopy in all provinces.

Exposure duration. Exposure duration is the total amount of time (s) that the x-ray beam was turned on during one fluoroscopy examination. A total of 88 physicians (23 in Nova Scotia and 65 in other provinces) provided information on minimum and maximum exposure duration in fluoroscopic examinations related to pneumothorax procedures, indicating that a single fluoroscopic examination could have lasted between 1 and 300 s. However, physicians were not asked to report average or typical exposure durations. Thus, different methods were used in this analysis to estimate average exposure durations in Nova Scotia and other provinces.

The minimum and maximum exposure durations reported by each physician were assumed to represent the 1^{st} and 99^{th} percentiles of a probability distribution of possible exposure durations used by that physician. The shape of each distribution was assumed to be either lognormal or normal. The average of each assumed distribution was considered to be the best estimate of the exposure duration for each physician.

Under the assumption of lognormal distributions, average exposure durations among all physicians ranged from 3 to 57 s in Nova Scotia and from 2 to 86 s in other provinces. The mean weighted by the number of years of experience of the physicians is 13 s in Nova Scotia and 18 s in other provinces. Under the assumption of normal distributions, average exposure durations in

Nova Scotia ranged from 3 to 153 s, with a weighted mean of 17 s. In other provinces, average exposure durations ranged from 2 to 155 s, with a weighted mean of 22 s.

When data points from two physicians who reported the largest maximum exposure durations of 300 s were eliminated, the resulting weighted means in Nova Scotia and other provinces were 12 s and 17 s under the lognormal assumption, and 14 s and 22 s under the normal assumption, respectively. Lastly, when data were limited to physicians for whom the average exposure duration was between the 15^{th} and 85^{th} percentiles of average values across all physicians (15 physicians in Nova Scotia and 40 physicians in other provinces), weighted average durations in Nova Scotia and other provinces were 10 s and 14 s under the assumption of lognormality and 12 s and 17 s under the assumption of normality, respectively.

Given the wide ranges of reported minimum and maximum exposure durations, it is assumed that estimates of average exposure durations based on an assumption of lognormal distributions are more appropriate. Estimates using the different methods described above indicate average exposure durations in the range of 10 to 17 s in Nova Scotia and 14 to 24 s in other provinces. These ranges of average exposure durations in the two regions overlap. Given that physicians were asked questions only about minimum and maximum exposure duration, and given that, in general, there is no biological reason for average exposure durations representing many physicians and several decades to be different, the uncertainty in average exposure durations is assumed to be represented by uniform probability distributions with ranges of 10 to 24 s (mean = 17 s) for both Nova Scotia and other provinces. Since responses from physicians' interviews focused on pneumothorax procedures only, a wider uniform distribution with a range of 8 to 26 s was assumed for pneumoperitoneum and chest aspirations.

Based on data from interviews with physicians in tuberculosis sanatoria in Massachusetts, Boice et al. (1978) (*10*) reported an average exposure duration per fluoroscopy exam of about 15 s, with a range of 3 to 60 s. Similar exposure durations for chest fluoroscopies in the late 1960s and early 1970s (mean of 23 s, standard deviation of 15 s, and range of 11 to 52 s) were reported by Jankowski (1972) (*9*). These ranges represent the variability in average exposure durations used by various physicians. The ranges of average exposure durations obtained from physician interviews are comparable to the values reported in the literature.

The selected exposure durations are sampled independently between Nova Scotia and other provinces, but are assumed to apply correlated at all ages and in all years of treatment, because the duration of a fluoroscopic exam was related more to the purpose and conditions of the exam than to age or year of treatment. The exposure duration presumably differed from exam to exam depending on how well a physician's eyes were adjusted to darkness, and physicians presumably differed in how thoroughly they performed an exam.

Patient orientation. Fluoroscopic viewings of tuberculosis patients were carried out in either anterior-posterior (AP) or posterior-anterior (PA) orientation, as opposed to general fluoroscopy examinations of the chest, which were more commonly performed in PA orientation (*4*). In AP orientation, the patient faces the x-ray tube and is irradiated from front to back. In PA orientation, the patient faces the examiner and is irradiated from back to front.

A total of 82 physicians (22 in Nova Scotia and 60 in other provinces) provided information on the fraction of time that AP or PA orientation was used. Most physicians in Nova Scotia (73%) reported that they always used AP orientation, whereas most physicians in other provinces (78%) reported that they always used PA orientation. Several physicians in both

regions reported that they used both orientations and provided a fraction of the time in which each orientation was used. The average fraction of exams in which AP orientation was used, weighted by the number of years of experience for each physician, was 0.65 in Nova Scotia and 0.08 in other provinces. The standard deviation of the weighted average was 0.12 in Nova Scotia and 0.04 elsewhere.

Interviews with physicians in sanatoria in Massachusetts indicated fractions of exams in AP and PA orientations in tuberculosis patients in the U.S. of 0.29 and 0.71, respectively (Boice et al., 1978) (*10*). However, reports of practices in sanatoria in Nova Scotia (*15, 17*) indicate that AP orientation was used preferentially for hygienic reasons, so that a patient who coughed would not spray infective droplets toward the examiner. Mackenzie (1965) (*15*) also acknowledged that the manner in which fluoroscopic viewings of tuberculosis patients took place varied from place to place in Canada and with the physician who carried out the exam.

Triangular distributions with minimum, mode and maximum values equal to 0.50, 0.65 and 0.95 for Nova Scotia, and 0.0, 0.08 and 0.16 in other provinces, respectively, indicated from physician interviews as described above, are used to represent the uncertainty in the fraction of exams in AP orientation for pneumothorax procedures. The fraction of exams in PA orientation was calculated as one minus the fraction in AP orientation. Since responses from physicians refer to pneumothorax, larger uncertainties were assigned to pneumoperitoneum and chest aspirations by allowing wider triangular distributions with minimum, mode, and maximum of 0.40, 0.65, 1.0 for Nova Scotia, and 0.0, 0.08, 0.20 for other provinces, respectively. The assumed distributions, which are applied to both sexes and all ages at exposure, are sampled independently between the two regions and between medical procedures.

Shuttering. Fluoroscopic examinations of the lungs in tuberculosis patients were carried out in most cases with open shutters, which allowed the physician to examine both lungs. Shuttering was used when the physician wanted to focus the beam on the diseased lung only. A total of 33 physicians (7 in Nova Scotia and 26 in other provinces) provided information about the fraction of time shuttering was used. In Nova Scotia, 6 physicians reported that shuttering was never used, and one physician reported that shuttering was used in 5% of cases. The average fraction of time shuttering was used in Nova Scotia, weighted by the years of experience of the physicians, was 0.01 with a standard deviation of the weighted average of 0.01. Physicians in other provinces reported somewhat higher fractions than in Nova Scotia. The weighted average fraction of the time shuttering was used in other provinces was 0.13 with a standard deviation of 0.05.

Boice et al. (1978) (*10*) reported that 69% of physicians in sanatoria in Massachusetts performed fluoroscopic examinations with shutters open and 81% scanned the opposite lung to determine whether the tuberculosis had spread.

Uniform distributions with bounds 0 and 0.02 in Nova Scotia and 0.03 and 0.23 in other provinces were used to describe the uncertainty in the fraction of time shuttering was applied for both pneumothorax and chest aspiration procedures. Since pneumoperitoneum induces a collapse of the lower lobes of both lungs, it is reasonable to assume that the examiner always looked at both lungs during an air refill and shuttering was not used. The separate probability distributions in Nova Scotia and other provinces, which are applied to both sexes and all ages at exposure, are sampled independently between the two regions and between medical procedures.

Fluoroscopies after refill. Pneumothorax and pneumoperitoneum procedures required refills with air every one to two weeks to maintain a collapsed lung. Fluoroscopic examination of

the patient was commonly performed before air was inserted, and, in some cases, after air insertion as well. A total of 75 physicians (22 in Nova Scotia and 53 in other provinces) provided information about the occurrence of a second fluoroscopy after air refill. In Nova Scotia, most physicians indicated that a second exam was always performed, and a few physicians indicated that it was performed in >80 % of cases. The average fraction of the time fluoroscopy was used after refill, weighted by the years of experience of the physician, was 0.98, which means that patients in Nova Scotia received, on average, 1.98 fluoroscopy examinations during each medical procedure involving air refill. In other provinces, responses from physicians were mixed, with reported fractions of time a second fluoroscopy was performed ranging from 0 to 1. The average fraction of the time fluoroscopy was performed after refill, weighted by the years of experience of each physician, was 0.18; i.e., patients in other provinces received, on average, 1.18 fluoroscopy examinations per refill. These data indicate a significant difference between the two regions. The standard deviation of the weighted mean is 0.015 in Nova Scotia and 0.057 in other provinces.

Mackenzie (1965) (*15*) noted that fluoroscopy after a refill was a common practice in tuberculosis sanatoria in Nova Scotia, but that use of that practice varied in other provinces. In Massachusetts (*10*), physicians reported that only about 1% of patients received a second fluoroscopy exam after a refill.

A uniform probability distribution between 0.95 and 1.0 was assumed to describe the uncertainty in this parameter in Nova Scotia, given that the reported values are close to 1.0 and lie within a narrow range. In other provinces, a triangular probability distribution with minimum at 0.06, mode at 0.18, and maximum at 0.30 is assumed. These distributions, which are applied

to both sexes and all ages at exposure, are sampled independently between the two regions and the procedures of interest.

This parameter is used in calculating organ doses from pneumothorax and pneumoperitoneum but not chest aspiration, which does not involve refills with air. Also, this parameter was not used when medical records indicate that a patient received fluoroscopy without a refill.

In effect, this parameter increases the fluoroscopy time during a medical procedure. The number of fluoroscopy examinations per procedure is applied as a multiplier in calculations of organ doses. The exposure duration per fluoroscopic examination multiplied by the number of examinations per procedure can be regarded as an "effective" average exposure duration. For pneumothorax, the means and 95% CIs of the effective average exposure durations are 34 (95% CI: 21, 47) s in Nova Scotia and 20 (95% CI: 12, 28) s in other provinces.

Dose Conversion Coefficients

A dose conversion coefficient (DCC) is defined as the absorbed dose (Gy) in a specified tissue per air kerma (Gy) at skin entrance. Calculation of this parameter accounts for the attenuation of incident radiation as it passes through the body and the energy deposition in a tissue of interest. Dose conversion coefficients specially developed for this analysis are based on calculations in the most recent hybrid computational phantoms (*27, 28*), and were obtained from radiation transport calculations carried out using the MCNPX v.2.7.0 system, based on x-ray spectra generated by Spektr computational tool (*29-31*). Dose conversion coefficients for chest fluoroscopy (i.e., pneumothorax and chest aspiration) and fluoroscopic procedures associated with pneumoperitoneum, in which the beam is directed at the upper abdomen, were calculated based on the following assumptions about relevant parameters:

1. Parameters related to patient
    a. Age (1, 5, 10, 15, adult)
    b. Sex (male, female)
    c. Average sex- and age-dependent heights and body masses representative of a mid-20th century Canadian population, with masses adjusted downwards for patients with tuberculosis
    d. Orientation (AP, PA)

2. Parameters related to operation of fluoroscopes
    a. Size of x-ray field at image receptor (width of 40.6 cm, height of 27.9 cm)
    b. Location of center of incident beam relative to anatomical landmarks
        - chest: 6.2 cm above xiphoid process in adults
        - abdomen: 2.0 cm below xiphoid process in adults
        - distances scaled down at ages younger than adults
    c. Distance from tube focal spot to panel (32.5 cm)
    d. Filtration (no added filtration, 1 mm Al added filtration)
    e. Tube voltage (50, 75, 100 kV)
    f. Shuttering (right or left lung)

Dose conversion coefficients used in this analysis are intended to represent average values for a subgroup of individuals (e.g., adult males who received a chest fluoroscopic exam in PA orientation with no added filtration). Uncertainties in the average DCCs in defined subgroups account for uncertainties in (1) the tube voltage and total filtration in operation of a fluoroscope,

(2) the position of the incident beam, (3) average heights and body masses of patients, and (4) radiation transport calculations. These sources of uncertainty are discussed below.

Tube voltage and total filtration. Dose conversion coefficients depend on the spectrum of incident x rays, which is determined by the tube voltage and total filtration in operation of a fluoroscope. Monte Carlo sampling from probability distributions of uncertain tube voltages and total filtrations is used to generate probability distributions of average dose coefficients based on the relationship that calculated coefficients increase linearly with increasing tube voltage at a specified total filtration (*28*). Organ doses and their uncertainties are estimated using these voltage-dependent dose coefficients and an accounting of the uncertainty in total filtration in some years.

Beam position. There is uncertainty in the location of the beam in any exam, as physicians may have centered the beam in slightly different positions from the assumed average position or changed the position during an exam. Small horizontal shifts in beam position are unimportant when the width of the beam is greater than the width of the body. However, small vertical shifts can affect doses to various organs, especially organs that are located at the upper or lower edge of the field of view of the incident beam. An analysis was carried out to estimate changes in dose conversion coefficients due to a vertical shift of the center of the beam of ± 2.5 cm, while assuming organs remain in a fixed position. These estimated changes in dose conversion coefficients are also representative of the situation when the beam position remains fixed, but organs shift, for example due to lung inspiration, natural lung collapse, or induction of artificial pneumothorax in tuberculosis patients. The magnitude of the assumed shift (± 2.5 cm)

is considered to be a reasonable representation of the uncertainty in the average relative position of beam and organs.

For organs that remain in the field of view of the incident beam, variations in dose conversion coefficients due to the assumed vertical displacement are several percent. In chest fluoroscopy, these organs include the lungs, female breast, and heart. For organs at the lower and upper edges of the field of view of the incident beam (e.g., stomach), variations in dose conversion coefficients can be a factor of two or larger, depending on tube voltage and a patient's age and sex. For organs located far outside the field of view (e.g., prostate or ovaries in chest fluoroscopy), variations in dose conversion coefficients can be as much as 30 to 40%.

The uncertainty in a DCC due to the vertical displacement of the beam is applied as a multiplicative factor in the form of a triangular distribution with mode at the calculated value for the nominal position of the beam and minimum and maximum values at the values of the DCC obtained when the beam is shifted up or down by 2.5 cm (*28*).

Body masses and heights in tuberculosis patients. A special research effort was dedicated to estimating typical body masses and heights of tuberculosis patients in Canada in the period 1930 to 1969, based on Canadian national survey data and extensive literature review. Results of that research, which are described in a separate report (32), were summarized in two parts: (1) selection or estimation of average heights and body masses in the Canadian white population during the period of interest; and (2) estimation of any differences in body masses between tuberculosis patients and healthy individuals. The latter were used as multiplicative scaling factors to adjust body masses at each age in the general population. The derived scaling factors are 1.0 in males of ages 0 to 5 and females ages 0 to 7, 0.95 in males of ages 6 to 7, and 0.9 in males and

females of ages 8 and older. Average body masses and heights of males and females in the general Canadian white population were obtained from a large sample and, thus, have a negligible uncertainty. However, the average scaling factors are uncertain, leading to an uncertainty in average body masses in tuberculosis patients of about ± 6% or less.

Several sources of information were used to assess the uncertainty in organ DCCs due to the uncertainty in an average body mass, including the DCCs used in this analysis and in several studies (33-35) which assessed the variation in DCCs for various organs with variations in body size and exposure conditions. Those studies indicate that the uncertainty in a calculated DCC due to the uncertainty in average body masses in tuberculosis patients in Canada is about 10%. To account for the additional uncertainty arising from variations in average height and any differences between exposure conditions in the studies noted above and the average exposure conditions for CFCS patients (e.g., changes in position of organs, level of lung inspiration or collapse and consolidation of airways due to tuberculosis), an uncertainty of ±20% is assumed in this analysis for all organs. This uncertainty in DCCs is represented by a multiplicative factor in the form of a triangular probability distribution with minimum at 0.8, mode at 1.0, and maximum at 1.2. This uncertainty is assumed to be fully correlated across all ages, but independent in males and females.

Statistical uncertainties in radiation transport. Dose conversion coefficients that are estimated using Monte-Carlo radiation transport calculations have uncertainties arising from the statistical nature of the Monte-Carlo sampling process. Statistical uncertainties in DCCs for organs in the field of view of an incident beam (lungs, female breast, heart, active bone marrow), defined as one standard deviation divided by the mean, are about 0.05%. These uncertainties are

negligible compared to other sources of uncertainty. Statistical uncertainties in DCCs for small organs located far outside the beam (e.g., prostate in chest fluoroscopy or thyroid in abdominal fluoroscopy) can be 50% or greater. However, dose conversion coefficients for such organs are much lower, because far fewer photons reach those organs.

Number of Medical Procedures

Organ doses to CFCS patients are estimated based on the number of medical procedures involving radiation exposure for each patient and a patient's age at the time of each procedure. The cohort data contain one or multiple treatment records for each patient in the study cohort. The records include the type of procedure (e.g., pneumothorax), dates (month, day, and year) when a series of treatments started and ended, and the total number of procedures during that period; those records did not include the dates of any procedure or the medical institution where procedures were administered. In some records, a treatment rate prescribed by a medical doctor was available (e.g., one refill with air per week for a patient with an artificially induced pneumothorax). Patients may have had multiple courses of treatment (e.g., pneumothorax in 1947 and 1948 and pneumoperitoneum in 1950). Each procedure during a course of treatment may have involved one or sometimes two fluoroscopy examinations (i.e., one before and one after a refill with air).

For some patients the cohort data were incomplete. Missing data possibly included a missing month or year of the start date or of the end date, and/or missing treatment information (number of procedures or prescribed treatment rate). Any part of a treatment record that was missing was imputed based on average treatment rates and treatment durations estimated for each medical procedure from patients in the cohort for whom the treatment records were complete.

These imputations of missing data could introduce uncertainty in the estimated number of procedures received by each patient.

To account for uncertainty in the estimated number of procedures, each treatment record was assigned a completeness score from 1 to 9, with 1 representing a complete record and 9 representing a record missing all data. Completeness scores for each treatment record were averaged and rounded up to the nearest integer for a given procedure type and patient, allowing patients to be grouped in uncertainty categories 1 to 9. For each procedure type (pneumothorax, pneumoperitoneum, chest aspirations), more than 65% of patients were in uncertainty categories 1 through 4 (complete and nearly complete data), and more than 85% of patients were in categories 1 through 6 (complete, nearly complete and containing essential information). For pneumothorax procedures with refill, which make up over 60% of all procedures, the percentages of patients in uncertainty categories 1 through 9 were: 29%, 12%, 12%, 17%, 10%, 9%, 5%, 5%, and 0.5%, respectively.

A lognormal probability distribution was assigned to represent the uncertainty in the number of procedures per patient, by procedure type, to all patients in the 9 uncertainty categories. The lognormal distributions have a mean of 1.0 and standard deviations equal to 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.4, 0.45 and 0.5, for the 9 categories, respectively. These standard deviations were chosen by accounting for typical treatment methods used in tuberculosis sanatoria at the time. The average rate of pneumothorax and pneumoperitoneum was one refill every 1 to 2 weeks (2 to 4 refills per month), with an expected average duration of treatment of 2 to 5 y. Such a treatment protocol would result in a range of approximately 50 to 260 total procedures (a variation of a factor of about 5, equivalent to the width of a 95% CI of a lognormal distribution with a standard deviation of 0.44). For the worst-case scenario (uncertainty category

9), which is the case of a patient who is missing both the duration of treatment and any treatment information (including number of procedures or prescribed treatment rate), a standard deviation of 0.5 was assigned. The uncertainty distribution defined for this scenario has a 95% CI of 0.36 to 2.2, ranging by a factor of approximately 6. Progressively lower standard deviations were assigned to the rest of the uncertainty categories, based on the assumption that categories of patients which include the number of procedures can be considered more reliable and thus having less uncertainty than categories of patients for which the number of procedures was imputed. Uncertainty categories 8 and 7 were assigned slightly less uncertainty than uncertainty code 9 (standard deviations of 0.45 and 0.40 respectively), because the number of procedures, prescribed treatment rate, and some dates were missing. Patients in uncertainty categories 2 through 6 were assigned still lower standard deviations, ranging from 0.05 to 0.25, because the numbers of procedures, the prescribed treatment rates or the treatment dates are known.

Each probability distribution was applied as multiplicative factor to the number of procedures of a given type received by a patient in a respective uncertainty category. The distributions were assumed to be correlated for all patients sharing the same uncertainty category. For example, the uncertainty in the imputed average number of procedures for all patients with an uncertainty category of 3 is described by samples from a single lognormal distribution with a mean of 1 and a standard deviation of 0.1.

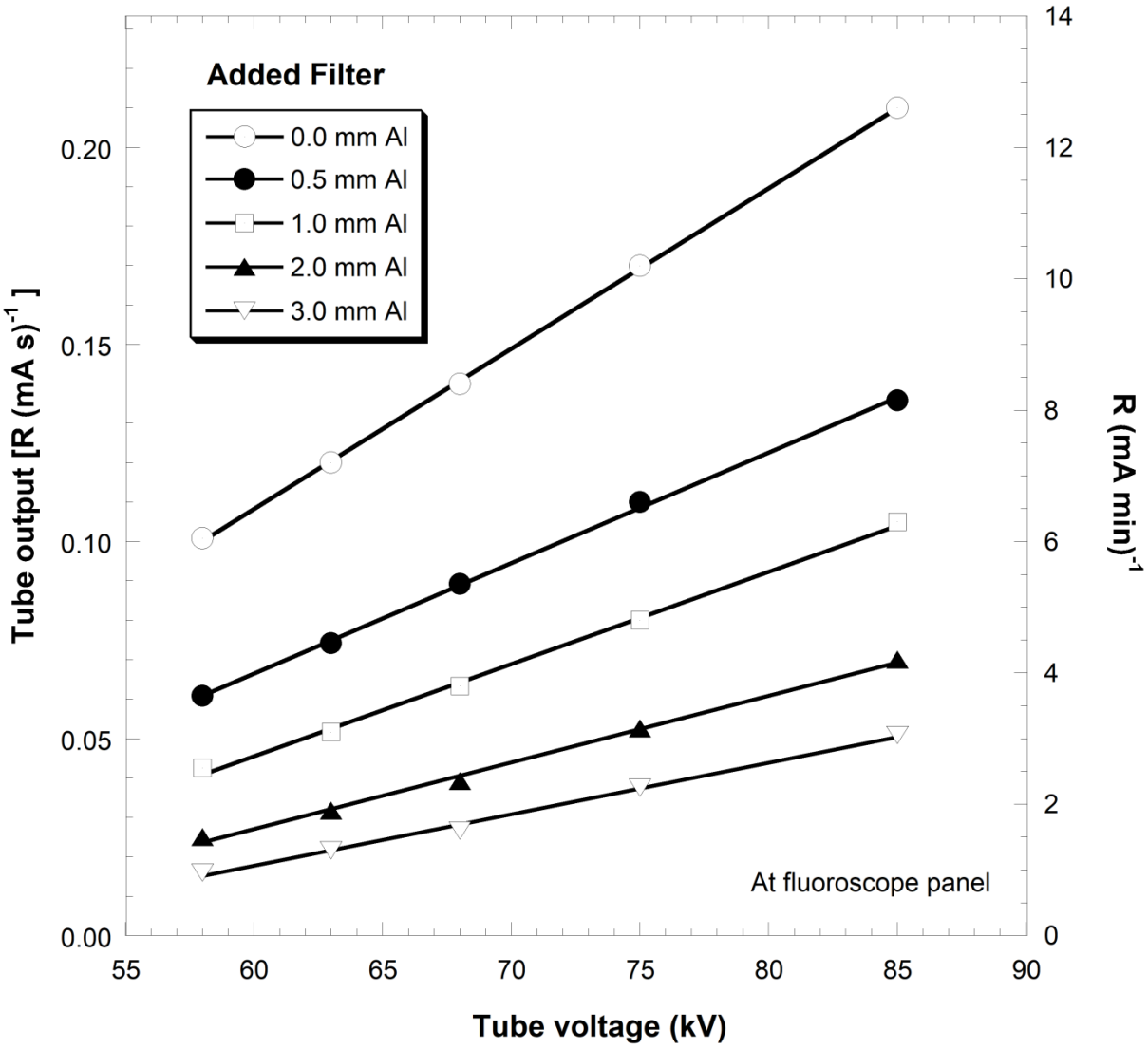

FIG. A1. Measured tube output at fluoroscope panel, for different tube voltages and added filtrations; SI units on left y-axis, non-conventional units on right y-axis (*10*).

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APPENDIX B – Mathematical Formulation

Average organ doses to each patient were estimated based on (1) estimated average organ doses per procedure of each type and (2) the number of procedures of each type (e.g., pneumothorax) reported in medical records. Estimated organ doses per procedure account for the fraction of procedures in which shuttering of the beam occurred and the fraction of procedures in each orientation of the patient. Organ doses were calculated for each medical procedure separately based on estimates of exposure durations and the procedure-specific location of the incident beam (chest vs. upper abdominal areas). Doses depend on a patient's sex and age at time of a procedure. During a medical procedure that involved a refill with air, a patient may have received one or two fluoroscopic exams (i.e., one before refill and, sometimes, one after refill).

Estimates of organ doses per examination in any procedure were based on estimates of exposure in air (R) at skin entrance, which were obtained by multiplying the exposure rate in air (R s^{-1}) by the exposure duration (s) for a single fluoroscopy procedure. The exposure rate in air is the product of the tube current I (mA) and the tube output, denoted by Y [R (mA s)$^{-1}$], at skin entrance, which depends on the tube voltage and total filtration of the x-ray beam. Tube output was assumed to vary with distance from the tube anode (d) as $1/d^2$. Uncertainties in tube output at skin entrance introduced by uncertainties in distance from tube anode to skin entrance and by observed variability of tube outputs are discussed in Appendix A.

The total exposure in air per examination (R) was converted to air kerma[3] at skin entrance (Gy) and then to an organ absorbed dose by multiplying by a dose conversion coefficient, which is an organ dose (Gy) per unit air kerma at skin entrance (36). Dose conversion coefficients depend on (1) a patient's age, sex, and orientation relative to the x-ray

[3] Air kerma and absorbed dose in air at skin entrance can be assumed to be equal for the x-ray energies and source-to-skin distance of interest (*33*).

tube and (2) the tube voltage, total filtration, and, to a lesser extent, the source-to-skin distance. FLUXOR uses organ-specific dose conversion coefficients calculated based on the most recent human computational phantoms, adjusted to represent average body masses and heights of CFCS tuberculosis patients (*27, 28)*.

An absorbed organ dose per exam ($D_{i,j,p.k}$; Gy) for a given medical procedure (p), patient orientation (i), shuttering choice (j), and year of an exam (k) was calculated as the product of the tube output (Y_k) under filtration conditions (f), tube current (I_p), procedure-specific exposure duration (ED_p; s), and organ-, sex (s)- and age (a)-specific dose conversion coefficient ($DCC_{i,j,p,k}$; Gy Gy^{-1}):

$$D_{i,j,p,k} = Y_k(V_p, f, d) \cdot I_p \cdot ED_p \cdot DCC_{i,j,p,k}(V_p, f, s, a)$$

To account for the two possible patient orientations (i) and shuttering conditions (j), the organ dose from a single examination ($D_{p,k}$; Gy) during a given medical procedure (p) in a given year (k) was calculated as a weighted average of organ doses ($D_{i,j,p.k}$) from single exams administered with or without shuttering of the beam and in a given patient orientation (AP or PA in fluoroscopic exams of the lungs).

$$D_{p,k} = \left[\sum_{\substack{j=1 \\ Shutter}}^{2} g_j \left(\sum_{\substack{i=1 \\ Orientation}}^{2} r_i \cdot D_{i,j,p,k} \right) \right]$$

In this equation, parameters r_i and g_j represent the fractions of exams administered in patient orientation i and shuttering conditions j, respectively.

The organ dose in any year from a particular type of medical procedure was calculated as the product of the number of fluoroscopic procedures in that year ($N_{p,k}$), the organ dose from a single examination ($D_{p,k}$) and the number of examinations (n_x) per procedure. In medical

procedures involving a refill with air, fluoroscopic examinations were carried out before, and sometimes after, air was inserted ($n_x \geq 1$). Only one examination was given if a refill with air was not necessary ($n_x = 1$).

In each year, an organ dose (D_k) was calculated as the sum of organ doses from all procedures (p) in that year.

$$D_k = \sum_{\substack{p \\ procedure}} n_x \cdot N_{p,k} \cdot D_{p,k}$$

Finally, a patient's total organ dose, D, was obtained as the sum of doses in each year (D_k):

$$D = \sum_{\substack{k \\ year}} D_k$$

The approach to estimating organ doses from fluoroscopic exams described above also applies, with some modifications, in estimating organ doses from chest radiographic exams. In chest radiography, the exposure duration was combined with the tube current, with the combined parameter referred to as the tube-current exposure-time product (*1*), and shuttering of the beam was not used. In GI series exams four oblique patient orientations were assumed in addition to AP and PA (*2*).

Sensitivity analyses were carried out to determine the relative contribution of the uncertainty in each parameter to the uncertainty in the dose per procedure, for various procedures. The relative contribution, often referred to as the "importance" of each parameter, was measured by the square of the rank-order correlation between the Monte Carlo sample of the dose per procedure and the sample of each parameter (37-40). This method is a robust measure

of the uncertainty contribution because it is insensitive to extreme values and skewed distributions.

APPENDIX C – Additional Results

TABLE C1 Average Doses (mGy) from a Single Medical Procedure

Procedure [a] /		Lungs		Active bone marrow		Breast	Heart Wall	
Province	**Conditions [b]**	**Males**	**Females**	**Males**	**Females**	**Females**	**Males**	**Females**
PNEUMOTHORAX								
Nova Scotia	No filter	22 (8.5, 42)	25 (9.9, 50)	3.6 (1.4, 7.2)	3.9 (1.5, 7.5)	56 (21, 110)	25 (8.8, 49)	32 (12, 62)
	Filter added	16 (8.1, 27)	18 (9.1, 32)	2.7 (1.3, 4.7)	2.8 (1.4, 4.9)	36 (17, 64)	18 (8.8, 32)	23 (11, 39)
Other Provinces	No filter	8.9 (3.4, 17)	8.6 (3.3, 17)	2.6 (0.99, 5)	2.6 (1.0, 5.0)	4.5 (1.3, 9.9)	4.3 (1.7, 8.8)	4.3 (1.6, 8.8)
	Filter added	6.6 (3.2, 11)	6.4 (3.1, 12)	1.9 (0.9, 3.4)	1.9 (0.92, 3.4)	3.0 (1.1, 6.3)	3.3 (1.6, 6.0)	3.2 (1.4, 5.9)
CHEST ASPIRATIONS								
Nova Scotia	No filter	11 (3.6, 24)	13 (4.3, 28)	1.8 (0.62, 3.8)	1.9 (0.64, 3.9)	29 (9.6, 59)	13 (4.2, 28)	16 (5.4, 35)
	Filter added	8.2 (3.2, 16)	9.3 (3.6, 18)	1.3 (0.51, 2.5)	1.4 (0.54, 2.6)	19 (7.4, 37)	9.4 (3.6, 18)	12 (4.4, 23)
Other Provinces	No filter	7.6 (2.7, 16)	7.4 (2.6, 15)	2.2 (0.68, 4.6)	2.2 (0.69, 4.5)	4.3 (1.1, 11)	3.8 (1.1, 8.3)	3.9 (1.1, 8.7)
	Filter added	5.7 (2.3, 11)	5.5 (2.2, 10)	1.6 (0.65, 3.1)	1.6 (0.65, 3)	2.9 (0.79, 6.3)	2.9 (1.2, 6.0)	2.9 (1.1, 5.9)
PNEUMOPERITONEUM								
Nova Scotia	No filter	9.5 (3.2, 21)	10 (3.3, 21)	1.7 (0.51, 3.8)	1.8 (0.53, 3.9)	48 (16, 100)	14 (4.1, 30)	22 (5.9, 48)
	Filter added	7.0 (2.5, 14)	7.3 (2.8, 15)	1.2 (0.45, 2.5)	1.3 (0.47, 2.7)	32 (12, 61)	10 (4.0, 21)	16 (5.9, 33)
Other Provinces	No filter	5.4 (1.8, 11)	5.3 (1.6, 11)	1.7 (0.55, 3.8)	1.8 (0.6, 4.0)	4.7 (1.1, 12)	3.0 (0.89, 6.5)	3.6 (1.1, 8.3)
	Filter added	4.0 (1.6, 7.6)	3.9 (1.5, 7.5)	1.3 (0.5, 2.6)	1.3 (0.51, 2.7)	3.2 (0.82, 7.6)	2.2 (0.79, 5.0)	2.7 (0.97, 5.6)

[a] Pneumothorax and pneumoperitoneum including refill with air. Doses are for procedures received by adults. Doses to children from the same procedures, presented in ORRISK (2020) (*3*), are similar in magnitude. Reported values are means followed by 95% C.I. in parentheses.

[b] The use of an additional 1 mm Al tube filter was introduced between 1942 and 1951 (Table 3).

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Footnotes

[1] Two physicians reported tube currents of 30 and 35 mA. These values presumably were not possible in the period of interest, since the current was limited by the circuitry of the fluoroscope to 15 mA (*5*). Some fluoroscopes could have been limited to 20 or 25 mA, but probably not 30 mA or higher.

[2] Using a conversion factor of 0.00877 Gy R^{-1} (*23*).

[3] Air kerma and absorbed dose in air at skin entrance can be assumed to be equal for the x-ray energies and source-to-skin distance of interest (36).