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ESTIMATION OF EFFECTIVE DOSES FOR BARIUM MEAL FLUOROSCOPIC EXAMINATIONS

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***Abstract*:** The aim of the current study is to establish conversion coefficients (CCs) from dose-area product to effective dose for barium meal (BM) fluoroscopic examinations. The study is based on data collected at a major University hospital in St-Petersburg, Russia. The structure of the BM examinations was evaluated and a computational model for effective dose estimation, using PCXMC 2.0 software, was developed. Resulting values of CCs estimated in the study were comparable with previously published data for BM examinations.

***Keywords*:** effective dose, fluoroscopy, conversion coefficients, dose-area product

1. Introduction

Fluoroscopic examinations of the upper gastrointestinal tract (UGIT) contribute significantly to the collective dose from medical exposure, both in Russia (7% in 2015) [1] and European countries (2-50%) [2]. Barium meal (BM) examinations compose more than 40% of all fluoroscopic examinations in Russia [1], contributing 38% to the collective dose from fluoroscopic examinations. According to the Russian State law №3-FZ "On Radiation Safety of the Public" [3], each patient should be informed about the dose and the possible consequences (radiation detriment) from their medical exposure. That can be fulfilled through the use of effective dose, despite its limitations.

The most practical approach in assessing the effective dose is to use conversion coefficients (CCs), relating effective dose (E, mSv) with a measurable dose quantity such as the dose-area product (DAP, $cGy \cdot cm^2$). However, CCs are highly dependent on the exposure conditions (energy characteristics of the X-ray beam, exposure geometry and anatomic area of interest) [4]. On the contrary, only a limited set of CCs are usually available in national guidelines for certain exposure conditions [5].

In Russian practice CCs from DAP to E for BM examinations are presented in the Methodical Guidelines "Assessment of effective dose to the patients undergoing X-ray examinations" [6]. There the CCs are provided only for a single irradiation field size, limited range of tube voltages and for posterior-anterior (PA) projection, corresponding to the undercouch position of the X-ray tube. However, more than 60% of the fluoroscopy X-ray units in Russia are remotely controlled, with the standard overcouch position of the X-ray tube. Hence, it is necessary to update the existing CCs since they do not reflect the actual exposure conditions of the patients.
The aim of the current study was to estimate CCs for BM fluoroscopic examinations based on a data collection in a typical general practice hospital in St-Petersburg, Russia. That required to evaluate the structure of the selected fluoroscopic examinations, to collect the relevant examinations parameters, patient dose data, and to develop a model of patient exposure using the PCXMC 2.0 software [7].

2. Materials and methods

Data was collected in a surgical department of the St-Petersburg "Urban Mariinsky hospital" for 22 patients during a one-month period. All BM examinations were performed on a digital KRT-Electron (JSC "NIPK "Electron", Russia) X-ray unit. KRT-Electron is a remotely guided X-ray unit with an over-couch X-ray tube and a 12' CCD-matrix detector, commonly used for fluoroscopic examinations and these units composes up to 70% of all fluoroscopic X-ray units in St-

Petersburg. The following settings were used for BM examinations: focal-image distance 115 cm; total filtration of 5 mm Al with anti-scatter grid: 110 lines/inch, R=13:1, F = 180 cm. Imaging was performed using default vendor protocols with automated brightness control (ABC) without the digital image intensification. The X-ray unit was equipped with a DRK-1 clinical dosimeter (NPP "DOZA", Russia), calibrated using a reference ionization chamber prior to the study.

Patient positioning, examination structure, irradiation speed and total time of irradiation were selected by the radiologist (5 years of experience) individually for each patient based on his personal preferences, patient condition and preliminary diagnosis. Prior to the data collection the structure of examination was estimated based on the information from the radiologists.

Each examination was divided into a set of standardized fluoroscopy phases and X-ray images, specified by the examined anatomical region and the projection of patient exposure. The following data was collected for each fluoroscopy phase and for each X-ray image taken for each patient: patient position (standing, supine, prone, recumbent), projection, total fluoroscopy time (s), fluoroscopy speed (frames·s^{-1}), field size (cm·cm), average tube voltage (kV), total DAP (cGy·cm^2). Data was collected manually by the authors during the examination using dedicated spreadsheets. As the tube voltage varied in a real time, several (3-5) kV values were taken during the fluoroscopy and then averaged. All examinations were exported from the PACS and digitally recorded in DICOM format; these records were used for modelling the exposure of the patients in PCXMC 2.0 and for verification of the collected data.

Effective dose calculation was performed using the PCXMC 2.0 software [7]. The examinations were described as sets of fluoroscopic phases with the corresponding X-ray images taken. Each fluoroscopic phase, in turn, was described by a set of discrete irradiation fields, corresponding to the locations of the relevant organs and tissues. If there was no significant movement of the X-ray tube and only a single organ was irradiated (i.e. fluoroscopy of the stomach with contrast), the phase consisted of a single irradiation field. On the other hand, if different organs were exposed and the tube movement was significant (i.e. survey fluoroscopy of the esophagus), the phase consisted of several irradiation fields, each corresponding to a certain relevant anatomic location. Exposure parameters for each irradiation field within a single phase were considered to be constant. The following assumptions have been made: tube movement is linear with constant speed and the DAP is evenly distributed across the irradiation field. The number of irradiation fields and their locations for the specific fluoroscopic phases were selected in cooperation with the radiologists from the X-ray department of Mariinsky hospital (St-Petersburg, Russia) based on their experience and digital records of the completed examinations.

Coordinates for the selected irradiation fields were determined in PCXMC for each projection. A total of 8 projections were selected to describe the exposure of the patient: anteroposterior (AP); posteroanterior (PA); left and right lateral (LATL, LATR); left and right anterior and posterior oblique (LAO, RAO, LPA, RPO). For the simplicity of modelling all obliques laid in a transverse plane and formed a 45° angle with the AP/PA axis [5]. It should be noted that PCXMC 2.0 allows two approaches for defining the coordinates of the irradiation field coordinates: as a coordinate of the center of the relevant anatomic organ or as a coordinate of the corresponding point on the phantom surface. These two approaches were compared prior to the study: differences in estimated organ and effective doses did not exceed 5-7%. Hence, the first approach of defining the irradiation field was used for the convenience of modeling. Examples of the structure for different phases and coordinates of the centers of the corresponding irradiation fields are presented in Table 1 for the AP projection.

Table 1. Standardized fluoroscopic phases and the corresponding PCXMC 2.0 coordinates of the center of the irradiation fields.

Phase	Number of single irradiation fields	PCXMC coordinates of the center of the irradiation field		
		X	Y	Z
Survey fluoroscopy of the UGIT without barium contrast	1	0	2	70
	2	0	2	50
	3	0	2	43
	4	5	-2	40
	5	8	-7	35
Fluoroscopy of the esophagus with barium contrast	1	0	2	70
	2	0	2	50
	3	0	2	43
	4	5	-2	40
Fluoroscopy of the stomach with barium contrast	1	8	-7	35

For single X-ray images, it was assumed that the coordinates matched the coordinates of the last irradiation field for the corresponding fluoroscopic phase.

Effective doses and CCs were estimated for each patient using the standard adult phantom [7] (PCXMC default, 178.6 cm height and 73.2 kg body mass) both for the overcouch and undercouch X-ray tube position. For the latter geometry the study composition was kept the same, but the irradiation angles were inverted by 180°.

Effective doses were estimated based on DAP, using tissue weighting coefficients from ICRP Publication 60 [8]. For complex fluoroscopic phases (consisting of several irradiation fields), the DAP for each selected field was estimated using Equation 1:

$$DAP_{field} = DAP_{phase}/n,\ cGy{\cdot}cm^2 \quad (1)$$

where *n* is the number of irradiation fields for that phase (see Table 1).

Effective dose per phase was calculated as the sum of effective doses for each irradiation field. CCs were estimated for each phase for each patient for all projections using Equation 2:

$$K_{60} = E_{60} \cdot DAP/1000, \ \mu Sv \cdot cGy^{-1} \cdot cm^{-2} \quad (2)$$

where: E_{60} is the effective dose (mSv) per phase or per X-ray image, estimated using tissue weighting coefficients from ICRP Publication 60, *DAP* is the total dose-area product (cGy·cm^2) per phase or per X-ray image.

To estimate the CCs for the whole BM fluoroscopic examinations, the following method was used:

- Estimation of the effective doses and CCs for each fluoroscopic phase and X-ray image for each projection for each patient;
- Estimation of DAP contribution of each projection into the total DAP for the examination for the whole patient sample for the selected type of fluoroscopic examination;
- Estimation of the mean CC for the selected type of the fluoroscopic examination using Equation 3:

$$K_{60} = \sum_{projection} \frac{DAP_{projection}}{DAP_{total}} \times \times K_{60\,projection}, \ \mu Sv \cdot cGy^{-1} \cdot cm^{-2} \quad (3)$$

where $DAP_{projection}$ is the total DAP (cGy·cm^2) for all fluoroscopic phases and X-ray images for the selected projection for the whole patient sample for the selected type of fluoroscopic examination, DAP_{total} is the total DAP (cGy·cm^2) for all fluoroscopic phases and X-ray images for the whole patient sample for the selected type of fluoroscopic examination, $K_{60\ projection}$ is the CC for the selected projection for the whole patient sample, estimated using tissue weighting coefficients from ICRP Publication 60.

Statistical analysis of data was performed using Statistica 10 software.

3. Results

Overall data on BM examinations are presented in Table 2.

Table 2. Main parameters of BM examinations given as the mean±1 SD (min-max).

Number of fluoroscopy phases	8.7±3.4 (3-16)
Number of X-ray images taken	7.0±4.0 (0-15)
Tube voltage, kV	89±10 (61-127)
Fluoroscopy speed, frames/sec	5.0±1.7 (2.5-10)
Total fluoroscopy time per examination, s	199±89 (86-424)
Typical irradiation field size, cm·cm	28·28

Data on contribution of different fluoroscopic phases into a total DAP for BM examination is presented in Table 3.

Table 3. Contribution of different fluoroscopic phases into a total DAP and E for BM examinations given as the mean±1 SD (min-max).

Phase	Num-ber of phases	Dap per phase, cGy·cm^2	Effective dose per phase for overcouch tube position, mSv	Effective dose per phase for under-couch tube position, mSv
Survey fluoroscopy of the UGIT without barium contrast	1.0	276±285 (13-1056)	0.86±0.91 (0.05-3.38)	0.57±0.62 (0.03-2.31)
Fluoroscopy of the esophagus with barium contrast	1.0±1.0 (0-2)	477±505 (39-2013)	1.39±1.58 (0.14-6.86)	1.00±1.18 (0.10-4.78)
Fluoroscopy of the stomach with barium contrast	6.6±3.3 (1.0-14.0)	2704±2054 (264-8127)	6.67±5.62 (0.55-22.71)	5.56±4.58 (0.66-16.94)
Total examination	8.7±3.4 (3-16)	3392±2340 (316-10309)	8.72±6.44 (0.73-27.90)	6.99-5.20 (0.79-21.38)

Data on the contribution of different projections, corresponding to the overcouch and undercouch tube positions, and CCs for individual projections for BM examinations are presented in Table 4.

Table 4. Contribution from different projections to overcouch and undercouch tube positions and corresponding conversion coefficients for individual projections. Data is given as mean±1 SD (min-max).

Projection	Projection contribution for an overcouch tube position, %	Projection contribution for an undercouch tube position, %	CCs for individual projections, µSv·cGy^{-1}·cm^{-2}
AP	52%	12%	3.1±0.2 (2.6-3.8)
PA	12%	52%	1.9±0.2 (1.5-2.5)
LATL	13%	13%	1.9±0.2 (1.3-2.5)
LATR	6%	6%	1.0±0.1 (0.9-1.4)
LPO	-	-	-
RPO	-	-	-
LAO	8%	8%	1.7±0.2 (1.0-2.2)
RAO	8%	8%	1.7±0.2 (1.0-2.2)

The resulting CCs for BM examination for an overcouch and undercouch tube positions, were estimated as 2.6 and 2.0 µSv·cGy^{-1}·cm^{-2}, respectively.

4. Discussion

The proposed approach for estimation of the effective dose considers all important features of a fluoroscopic examination: 1) non-uniform structure of examination, 2) significant movement of the X-ray tube within a single fluoroscopic phase and 3) the variety of exposure geometries. Using standardized fluoroscopic phases with the defined coordinates of the irradiation fields allows a uniform approach to the effective dose estimation regardless of the structure of the examination.

As it is visible from Table 3, fluoroscopy phases with significant tube movement (survey fluoroscopy of the UGIT and fluoroscopy of the esophagus) contribute up to 70% (25% in average) to total DAP and total E for BM examination. Hence, it is important to consider such phases in the effective dose estimation.

A significant drawback of this method is the complicated process of data collection. Digital records of the fluoroscopic examinations are seldom used in Russian radiological practice. Hence, in order to evaluate the structure of an examination, it is necessary to collect all the relevant data manually during the examination or afterwards, by questioning the radiologists. That puts a significant limitation on an everyday use of the proposed method in hospitals. However, the proposed method can be used without any limitation for the optimization of fluoroscopic examinations.

Comparison of the estimated CCs with the published data for the BM examinations is presented in Table 5.

Table 5. Comparison of the conversion coefficients from DAP to E (ICRP 60) for BM examinations.

Source	CC for BM examination, $\mu Sv \cdot cGy^{-1} \cdot cm^{-2}$
Current study	Overcouch: 2.6 Undercouch: 2.0
Methodical guidance 2.6.1.2944-11 [6]	2.0
Delichas et al. [9]	3.4
Hart et al. [4]	2.0
Hart et al. [5]	1.7-2.4
Ciraj et al.[10]	1.9-2.4
Gyekye et al. [11]	3.2

The results of the current study are comparable with other published CCs for BM examinations (see Table 5). Differences in the absolute values of the CCs can be explained by various factors. Most important of these factors is the difference in the clinical protocols between the countries and hospitals. Another important factor is the difference between the models used for effective dose estimation, mainly selection of specific anatomic regions and projections to be included.

By definition, CCs depend on the patient irradiation geometry (anatomical region or organs of interest, projection, focal-image distance, irradiation field size) and energy characteristics of the X-ray beam (tube voltage, total filtration). All of these factors are influenced by the operator subjectivity and the characteristics of the X-ray unit, requiring consideration for an accurate dose estimation in a specific X-ray room or medical facility. In the current study, focal-image distance, filtration and field size were constant for all the patients. Hence, the variation in the CCs can be explained by the differences in the exposed anatomical region, projection and tube voltage. Relations between the CCs and tube voltage and exposed anatomic region are presented in Figures 1 and 2, respectively.

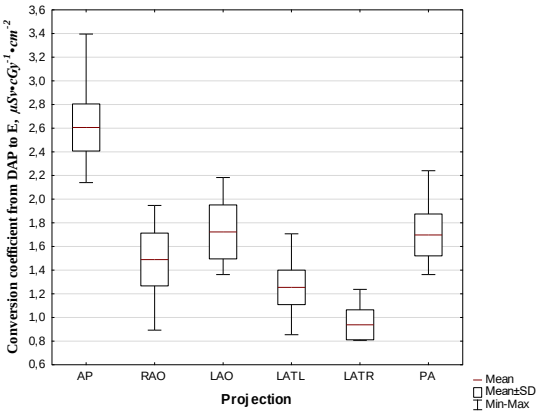

Fig. 1. Distributions of CCs ($\mu Sv \cdot cGy^{-1} \cdot cm^{-2}$) for different projections.

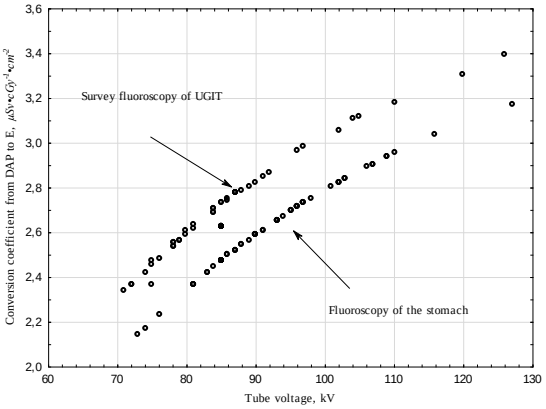

Fig. 2. Relation between the CCs ($\mu Sv \cdot cGy^{-1} \cdot cm^{-2}$) and tube voltage (kV) for two different fluoroscopic phases: survey fluoroscopy of UGIT and fluoroscopy of the stomach in AP projection.

It is visible from Table 4 and Fig. 1, that the direction of the projection has a significant impact on the CC value. Maximum values correspond to AP projection, and minimum values correspond to LATR projection. That can be explained by different depths of the main radiosensitive organs and tissues relative to the X-ray source. According to Fig. 2, an increase in tube voltage from 70 to 125 kV yields an increase in the CC by a factor of 1.5. CCs for the BM examinations were estimated considering the relative contribution of irradiation of the patient in different projections to a total DAP, for average tube voltage for the examination

To assess a single CC for a selected fluoroscopic examination it is necessary to consider the structure of the examination, geometry of patient exposure and the parameters of examinations and to apply a corresponding CC for each fluoroscopic phase of the complex examination based on the relative contribution

of different phases and projections into a total DAP for the examination.

5. Conclusions

Effective doses and the corresponding CCs for BM fluoroscopic examinations were calculated using PCXMC 2.0 software based on the data collected in a major St-Petersburg University hospital. The structure of the selected examinations was modelled individually for each patient. CCs were estimated for individual projections of patient irradiation and for the BM examination both for the over- and under couch X-ray tube positions. Comparison of the results of the study with the published data indicates some variations in the CCs values presented, which can be explained by the differences in clinical protocols and models used for the estimation of the effective dose.

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