European Journal of Radiology 85 (2016) 625–628

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Cumulative radiation exposure and associated cancer risk estimates for scoliosis patients: Impact of repetitive full spine radiography

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ARTICLE INFO

Article history:
Received 23 October 2015
Received in revised form
29 December 2015
Accepted 31 December 2015

Keyword:
Full spine scoliosis radiography
Cumulative effective dose
Cumulative cancer risk

ABSTRACT

Objective: To quantitatively evaluate the cumulative effective dose and associated cancer risk for scoliotic patients undergoing repetitive full spine radiography during their diagnosis and follow up periods.
Methods: Organ absorbed doses of full spine exposed scoliotic patients at different age were computer simulated with the use of PCXMC software. Gender specific effective dose was then calculated with the ICRP-103 approach. Values of lifetime attributable cancer risk for patients exposed at different age were calculated for both patient genders and for Asian and Western population. Mathematical fitting for effective dose and for lifetime attributable cancer risk, as function of exposed age, was analytically obtained to quantitatively estimate patient cumulated effective dose and cancer risk.
Results: The cumulative effective dose of full spine radiography with posteroanterior and lateral projection for patients exposed annually at age between 5 and 30 years using digital radiography system was calculated as 15 mSv. The corresponding cumulative lifetime attributable cancer risk for Asian and Western population was calculated as 0.08–0.17%. Female scoliotic patients would be at a statistically significant higher cumulated cancer risk than male patients under the same full spine radiography protocol.
Conclusion: We demonstrate the use of computer simulation and analytic formula to quantitatively obtain the cumulated effective dose and cancer risk at any age of exposure, both of which are valuable information to medical personnel and patients' parents concern about radiation safety in repetitive full spine radiography.

1. Introduction

Scoliosis is defined as a lateral curvature of the spine and radiography has been one of the standardized methods for diagnosis and for long term monitoring of the spine deformity [1]. Exposure to low dose ionizing radiation has been shown to increase the cancer risk in the life long studied cohort of Hiroshima and Nagasaki atomic bomb survivors [2]. This risk is particularly relevant to scoliotic children because children have a longer life expectance to develop complications and children are more susceptible to the effect of ionizing radiation than adult [3,4]. There have been many studies reporting patient effective dose from full spine radiography [5–8]. Furthermore the cumulative estimates of radiation dose and cancer risk due to repetitive X-ray radiography to scoliotic patients undergoing long term follow up has been attracting research interest [9,10]. We believe that provision of these cumulative estimates is meaningful for medical personnel to track patient radiation dose and to alleviate patients' parents concern about radiation risk along the course of follow up period with full spine radiography as part of the clinical assessment.

Recently, the estimates of cumulative effective dose and cancer risk have been regarded as important determinants in the cost-effectiveness decision analysis of a novel biplane X-ray imaging system (EOS^{TM}) when compared with standard X-ray system for the diagnosis and monitoring of orthopaedic conditions [11]. Because of lack of literature in cumulative effective dose and cancer risk of full spine radiography, decision making has been assumed that radiation induced cancer associated with per X-ray exposure is small. Nevertheless the comparison in cumulative effective dose and risk between the novel biplane and standard X-ray system has not yet been explored to quantify the health benefit from reduced radiation dose.

In the present study, we present generalized formula to obtain cumulative effective dose and cancer risk for repetitive full spine radiography using digital imaging system as a function of patient

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http://dx.doi.org/10.1016/j.ejrad.2015.12.032
0720-048X/

Table 1
Nominal X-ray tube operating parameter from the two X-ray machines as input data to the PCXMC software to simulate the organ absorbed doses in full spine radiography, namely, X-ray tube potential (kV_p), product of tube current in mA and exposure time in seconds (mAs) and number of projections (N). Mathematical phantoms of different age were used for the simulation. PA = posteroanterior.

Exposed	PA projection			Lateral projection		
Age (years)	kVp	mAs	N	kVp	mAs	N
5	68	8	1	75	8	1
10	78	20	2	88	32	2
15	82	25	2	90	40	2
20	84	25	2	92	40	2
25	84	25	2	92	40	2
30	84	25	2	92	40	2

age at exposure, gender and of patient population. It should enhance the literature content in scoliosis using repetitive ionizing radiation for cost-effectiveness analysis between conventional and novel imaging system such as EOS^{TM} [11].

2. Materials and methods

2.1. Computer simulation using PCXMC

The computer software PCXMC (version 2.0.1.3) [12], based on Monte Carlo simulation, has been used to simulate the organ absorbed doses for scoliotic patients with X-ray irradiation. Lee at al. demonstrated the usefulness of the PCXMC program to evaluate the effective dose in paediatric scoliosis radiography [13]. The PCXMC software requires the X-ray beam size, peak kilovoltage, X-ray source filtration and source to image receptor distance as input beam parameters. Mathematical phantoms of different age have been used to simulate organ absorbed doses in the current study.

2.2. Digital imaging systems and protocols for simulation

The nominal operating parameters of two digital X-ray machines (Machine 1: GE Discovery 650 of tube inherent filtration 1.1 mm Al; Machine 2: Carestream evolution of tube inherent filtration 0.9 mm Al), commonly used as radiography system to image scoliotic patients in our institute, have been input to the PCXMC software (Table 1). For scoliotic patients at age of 5 years old, full spine radiography can be covered with a single projection in each posteroanterior (PA) and lateral exposure. Patients at age of 6 years old and above undergoing full spine radiography are exposed by two projections at each PA and lateral exposure.

Table 2
Average dose results for the combined two imaging systems (GE Discovery 650 and Carestream evolution). E: effective dose, E_n: normalized effective dose.

	Average results for the combined two systems			
Exposed	E (mSv)		E_n [mSv/(kVp × mAs × N)]	
Age (Years)	Female	Male	Female	Male
5	0.22	0.20	1.91×10^{-4}	1.79×10^{-4}
10	0.84	0.80	9.72×10^{-5}	9.30×10^{-5}
15	0.69	0.65	6.12×10^{-5}	5.82×10^{-5}
20	0.66	0.62	5.80×10^{-5}	5.45×10^{-5}
25	0.62	0.58	5.41×10^{-5}	5.08×10^{-5}
30	0.60	0.57	5.25×10^{-5}	4.96×10^{-5}

2.2.1. Calculation of effective dose at any exposed age

The main steps in the PCXMC software are briefly described for patient effective dose (E) calculation according to ICRP-103 recommendations [14]:

$$E = \sum_{T} W_T \sum_{R} W_R D_{T,R} \tag{1}$$

where W_R is the radiation weighting factor (being unity for X-ray), $D_{T,R}$ is the absorbed dose to an organ or tissue as calculated by PCXMC software and W_T is the tissue weighting factor for organ or tissue T as listed in ICRP-103 recommendations. Organ absorbed doses in scoliotic irradiation, and hence the effective doses, are dependent on operating parameters of the imaging system and on the number of exposure projections (N). Therefore we defined the normalized effective dose E_n expressed as mSv per ($kV_p \times mAs \times N$) in that the calculated values of E (Eq. (1)) were normalized by the average values of kVp, of mAs and of N between PA and lateral projections of system. To obtain effective dose for scoliotic patient of different age undergoing full spine imaging, we performed mathematical fitting of the normalized effective dose (E_n) as a function of patient age, namely,

$$E_n = a \times \exp(-b \times \text{age}) + c \tag{2}$$

where a, b and c were fitted coefficients obtained by fitting normalized effective dose against patient age.

2.3. Calculation of cancer risk

We also made use of the PCXMC software to calculate the lifetime attributable risk (LAR) using the population-averaged dose-to-risk conversion factor of one cancer per 100,000 patients receiving a 100 mSv effective dose in accordance with the seventh Biological Effects of Ionization Radiation (BEIR VII) report [15]. LAR is defined as the sum of each year's excessive cancer probability after exposure and is a function of age at exposure, gender and population. Calculated values of LAR were then normalized by machine operation conditions and number of image projections ($kV_p \times mAs \times N$). To obtain LAR for scoliotic patient of different age undergoing full spine radiography, we performed mathematical fitting of the normalized LAR (LAR_n) as a function of patient age, namely,

$$LAR_n = x \times \exp(-y \times \text{age}) + z \tag{3}$$

where x, y and z were fitted coefficients obtained by fitting normalized LAR against patient age. Therefore LAR for any age at exposure can be calculated with the formula (Eq. (3)) for Asian and Western population.

2.4. Statistical analysis

Paired t-test for matched data was used to compare difference in effective dose and in LAR between female and male, between dose difference using the two imaging machines as described in the study, and between Asian and Western population. The software used was Statistica, version 11 (StatSoft, Tulsa, OK, USA). Values of $p \le 0.05$ were considered as statistically significant.

3. Results

3.1. Cumulative effective dose as function of imaging systems

Our results show that there is no statistically significant difference in cumulative E between patient genders ($p = 0.69$). Subgroup analysis shows that there is no statistically significant difference in cumulative E for female or for male patients between the two

Table 3
Fitted coefficients of normalized effective dose as function of age (Eq. (2)). Goodness of fit >0.99.

Fitted coefficient	E_n fitting	
	Female	Male
a	4.71×10^{-4}	4.24×10^{-4}
b	2.31×10^{-1}	2.24×10^{-1}
c	5.19×10^{-5}	4.87×10^{-5}

Table 4
Fitted coefficients of normalized LAR (LAR_n) as function of age for Asian and Western population (Eq. (3)). Goodness of fit >0.99.

Fitted coefficient	Asian: LAR_n fitting		Western: LAR_n fitting	
	Female	Male	Female	Male
x	8.70×10^{-6}	3.20×10^{-6}	9.27×10^{-6}	2.78×10^{-6}
y	2.07×10^{-1}	1.70×10^{-1}	2.38×10^{-1}	1.94×10^{-1}
z	3.30×10^{-7}	2.10×10^{-7}	4.32×10^{-7}	2.30×10^{-7}

imaging systems ($p = 0.64$ for female, $p = 0.65$ for male). Therefore we present the average cumulative effective dose from the two imaging machines as a combined system.

3.2. Cumulative effective dose as function of gender and age

Table 2 tabulates calculated effective dose E and normalized effective dose E_n as function of patient gender and age at exposure for the present study. The effective doses were normalized by the operating parameters of ($kV_p \times mAs \times N$). With the fitted normalized effective dose as a function of patient age at exposure (Eq. (2)), patient effective dose can therefore be obtained for patients of different age at exposure with the use of fitted coefficients (Table 3) and machine operating parameters. Cumulative effective dose can then be obtained by summing all effective doses that patients have previously undergone repetitive full spine radiography.

To present how cumulative effective dose is obtained, it is assumed that patients have their first scoliotic scan performed at 5 years old and then have annual follow up scan until their age of 30 years old. Fig. 1 shows the cumulative E of repetitively annual full spine radiography up to patient age of 30 years old for both genders. As an example for a female patient with her initial scoliotic full spine radiography at 5 years and with annual follow up scan, cumulative effective dose at her age of 30 years old can be directly read from Fig. 1 as 15.1 mSv. Similarly applied to a 5 years old boy, cumulative effective dose will be 14.3 mSv at his age of 30 years old. This clinically relevant example shows that even for an early onset scoliosis patient at 5 years old, the cumulative effective dose up to 30 years of age with annual follow up full spine radiography is about 15 mSv. Such cumulative doses are well below threshold level to induce deterministic effects in radiation safety [14]. As a comparison, the annual exposure to the human body due to natural background radiation is about 2.4 mSv [16]. Cumulative effective dose of 15 mSv is equivalent to less than 7 years of background radiation.

3.3. Cumulative LAR as function of gender, age and population

While the cumulative E for an early onset scoliosis patient is comparable to few years of background radiation dose, the LAR of cancer induction is the real concern to patients' parents. LAR is not only patient age and gender specific but also population dependent [17,18]. To generally apply the LAR to clinically operating conditions, analytic equation with fitted coefficients (Eq. (3)) for LAR_n as a function of age at exposure has been obtained for patient gender and population (Table 4).

To present an example how cumulative LAR is obtained at any age of exposure, it is assumed that a 5 years old Western girl has her first scoliotic scan performed and then she has her annual follow up scan until her age of 30 years old (Fig. 2). Cumulative LAR at her age of 30 years old can be directly read from Fig. 2 as 0.17% corresponding to one possible cancer induction case among 588 Western female scoliotic patients. Similarly for a 5 years old Western boy, his cumulative LAR is 0.09% at his age of 30 years old corresponding to one possible cancer induction case among 1111 Western male scoliotic patients.

It is interesting to note that there is no statistically significant difference in cumulative LAR for female patients between Asian and Western population ($p = 0.51$). Similarly, there is no statistically significant difference in cumulative LAR for male patients between Asian and Western population ($p = 0.50$)

However, scoliotic female patients of both Asian and Western population patients have statistically significant higher cumulative LAR than male patients of both populations undergoing the same repetitive full radiography ($p < 0.01$). This implies that scoliotic female patients have statistically significant higher cumulative LAR than male patients undergoing the same full spine radiography during the same follow up schedule.

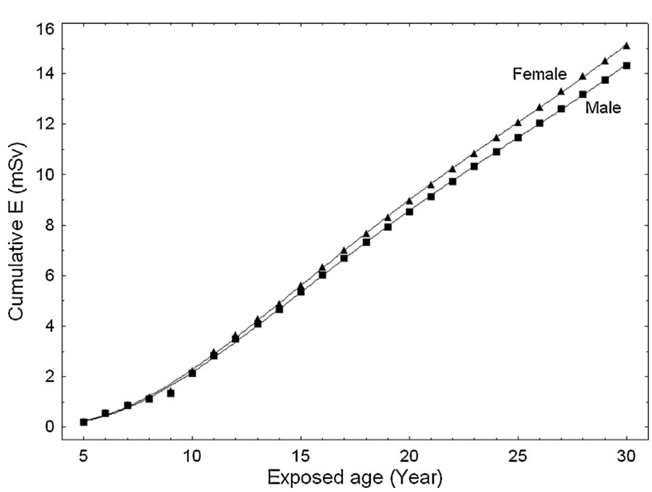

Fig. 1. Cumulated effective dose of repetitively annual full spine radiography up to 30 years of age.

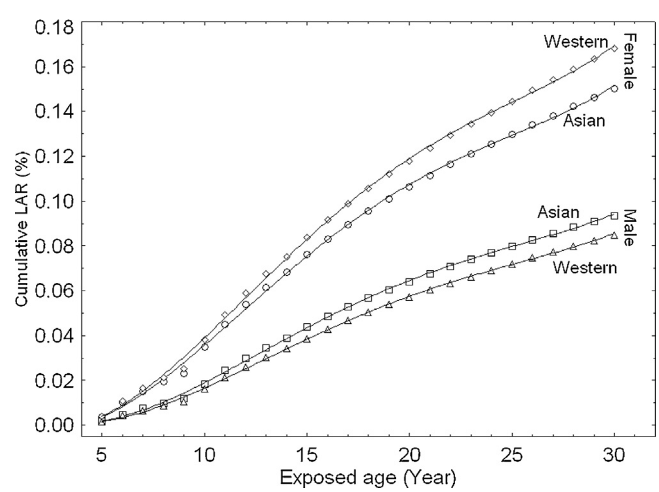

Fig. 2. Cumulated LAR for repetitively annual full spine radiography up to 30 years of age for Asian and Western population.

4. Discussion

Our results show that maximal cumulative effective dose from an early onset scoliotic patient undergoing annual full spine radiography from 5 years up to 30 years old is 15 mSv which is about 7 years background radiation exposure. The cumulative effective dose is increasing constantly from patient age of 15 years old at about 0.6 mSv per year for full spine radiography (Fig. 1). Therefore if patient clinical condition is stable, the time interval for periodic full spine radiography may be prolonged in order to minimize the cumulative effective dose.

There is no statistically significant difference in cumulative effective dose between patient genders and between the two digital imaging systems used in the current study. It implies that our results can be generally applicable to obtain patient effective dose at any age of exposure using digital imaging systems with similar operating conditions (Table 1).

For cumulative LAR up to 30 years old, female patients have cumulative LAR of 2 times higher than male patients (Fig. 2). In other words, female will have higher cancer induction probability than male if both genders have undergone the same full spine radiography monitoring protocol. This may be due to the incidence of breast cancer in female when compared to negligible incidence of breast cancer in male [19]. Again, it is suggested to prolong the repetitive imaging interval if patient clinical condition is stable.

Ronckers et al. studied cancer mortality in a cohort of 5573 females with scoliosis and other spine disorders diagnosed between 1912 and 1965, and who were exposed frequent diagnostic X-ray procedures [10]. Cancer mortality rate was reported 8% higher than expected. Our results of incidence rate of radiation induced cancer are relatively low when compared with results by Ronckers et al. [10]. Radiation doses from diagnostic radiographs have decreased substantially in the past as technology and procedures have changed, namely, use of digital radiography systems and use of posteroanterior imaging projection as part of the practice nowadays [4,20].

5. Conclusion

We have presented computer simulation results of effective dose and LAR at different age of exposure for both patient genders. Using the normalization technique to the calculated effective dose and LAR and using mathematical fitting method, cumulative effective dose and LAR can be obtained at any exposed age and patient gender. Female patients have higher cumulated LAR than male patients. Scoliotic scanning protocol should be tailored to reduce the dose and to optimize the repetitive scanning schedule in order to minimize the cumulated dose according to the As Low As Reasonably Achievable (ALARA) principle [14].

The current results also provide a literature reference for cumulative radiation dose and associated risk for digital imaging systems in the cost-effectiveness analysis model when compared with the EOS™ frontal/lateral simultaneous acquisition imaging system [11]. It would be interesting to have similar results for the EOS™ system in order to realize its dose reduction advantage.

Conflict of interest

All the authors of the manuscript entitled 'Cumulative radiation exposure and associated cancer risk estimates for scoliosis patients: impact of repetitive full spine radiography' declare that there is conflict of interest with regard to equipment, contrast, drug and other materials described in the study.

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