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

Martin Law*, Wang-Kei Ma, Damian Lau, Eva Chan, Lawrance Yip, Wendy Lam

Department of Radiology, Queen Mary Hospital, Hong Kong

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

* Corresponding author at: Department of Radiology, Queen Mary Hospital, 102 Pokfulam Road, Hong Kong. Fax: +852 2255 3872.
E-mail address: lawwm@ha.org.hk (M. Law).

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™ [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.

Exposed	Average results for the combined two systems			
	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]:

$$E = \sum_{T} W_T \sum_{R} W_R D_{T,R} \quad (1)$$

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,

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

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,

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

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 $p \leq 0.05$ 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