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Estimation of cancer risks due to chest radiotherapy treatment planning computed tomography (CT) simulations

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Abstract

The objective of our study was to determine organ and effective doses to estimate the lifetime attributable risk (LAR) of cancer incidence related to chest tomography simulations for Radiotherapy Treatment Planning (RTTP) using patient-specific information. Patient data from 70 chest CT scans were used to compute effective dose. The effective dose was calculated by two methods: first using ImPACT patient dosimetry calculator software using International Comission on Radiological Protection (ICRP103) weighting factors for a 70 kg patient and then applying related correction factors according to the patient's weight. Second using the scanner-derived dose-length product. LARs of cancer incidence was computed using the seven Biologic Effects of Ionizing Radiation (BEIR VII) report based on sex and age at each exposure. Mean±standard deviation values were 507.50±142.7 mGy.cm for DLP, 11.04±3.66mGy for CTDIvol, 46.88±6.65 cm for scan length. The mean±standard deviation value for the effective dose was 10.31±2.88mSv using ImPACT patient dosimetry calculator software and 8.62±2.42 mSv using the scanner-derived dose-length product. The mean ± SD of LAR of cancer incidence for all cancers, all solid cancers and leukemia were 65.49±28.54, 61.71±27.24, 6.62±2.46 cases per 100,000 individuals, respectively. Radiation exposure from the usage of CT for radiotherapy treatment planning (RTTP) causes non-negligible increases in lifetime attributable risk. The results of this study can be used as a guide by physicians to implement strategies based on the As Low As Reasonably Achievable (ALARA) princiciple that lead to a reduction dose without sacrificing diagnostic information.

Keywords Effective dose, Cancer induction risk, Chest CT scan, Lifetime attributable risks

Statements and Declarations

Conflict of interest All authors have no conflict of interest to declare.

Ethical approval This study was approved by the ethics committee of Kermanshah University of Medical Sciences (approval number: IR.KUMS.REC.1399.1164).

Informed consent Written informed consent was obtained from all the participants who voluntarily accepted to participate in the study.

Introduction

Since the advent of computed tomography (CT) in 1970, the annual use of CT scans in medical diagnosis has been increasing day by day. Nowadays, the number of CT scans in the United States has increased tenfold compared to the early days of its emergence (Huang et al. 2020). CT is a powerful tool for the early diagnosis of cardiovascular, chest, and abdominopelvic diseases, also trauma bleeding management, surgery, as well as planning of cancer treatment in radiotherapy. With the advancement of CT scanner technology, it became possible to cover a larger volume of the target in a shorter time, with higher resolution and lesser noise, while the radiation exposure to the patient increases in return (Pickhardt. 2018; Kubo et al. 2008; Karla et al. 2004; Tack and Gevenois 2004; Maher et al. 2004).

In terms of man-made ionizing radiation, medical radiology owns the largest share of approximately 96% (Manssor et al. 2015), and according to a report published in 2009 by the National Council on Radiation Protection and Measurement (NCRP) No. 160, the share of CT is 16% of the total medical imaging examination while the share of collective effective dose from all medical exposures is 49% (Schauer and Linton 2009). CT scan methods have an effective dose of about 5-20 times higher than routine conventional radiological examinations (Journy et al. 2014). The amount of dose received by the patient depends on various factors such as the type of CT scan filter, scan time, the patient's body width, radiation factors, and the protocol used (Asadinezhad et al. 2019).

CT scan and radiation therapy (3D conformal radiotherapy, intensity-modulated radiotherapy (IMRT) and other radiotherapy techniques) are strongly intertwined in the treatment planning workflow. In fact, in radiotherapy imaging, in addition to high-quality images, the visibility of the target anatomical structures and a correct mapping of CT number to density are necessary to accurately distinguish high-risk organs and gross tumor volume (GTV) for dosimetric calculation. Also, treatment planning CT scan is performed on a wider area compared to diagnostic CT scan. All of these factors may cause a higher CT dose in cancer patients (Dzierma et al. 2017; Ahmad et al. 2012). This high radiation dose of CT scan has raised concerns about the possibility of secondary cancer (Alkhorayef. 2018).

At present, dosimetric evaluations in CT scan examinations are usually based on two dosimetry parameters called the volume computed tomography dose index (CTDIvol) and the dose length product (DLP) (International Commission on Radiological Protection 2007). The CTDIvol quantity depends on several parameters such as scan field of view (FOV), exposure factors, pitch factor and collimation size, while the DLP quantity also depends on another parameter called scan length.

The aim of our study was to obtain the effective dose (using two methods) and organ dose in chest CT scan in relation to radiotherapy treatment planning. Afterwards, using the measured organ doses, the lifetime attributable risk (LAR) of cancer incidence in the chest’s organs at risk was

estimated by referring to the report of Biologic Effects of Ionizing Radiation VII (BEIR VII) (National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR) Report VII 2006).

Materials and methods

Data extraction

In this retrospective study, which was approved by the ethics committee of Kermanshah University of Medical Sciences (approval number: IR.KUMS.REC.1399.1164), the details of demographic data and dosimetric information were collected from the picture archiving and communication system (PACS) and CT scanner console of Shahid Rahimi Hospital between April 2021 and June 2022. All CT scan parameters were extracted along with patients' demographic information and analyzed using Microsoft Excel software.

According to previous studies (Bagherzadeh et al. 2018), the number of patients included in this study was 70 patients who underwent chest CT scan examination using a 16-slice CT scanner (Philips-Brilliance), of which 10 were male and 60 were female. The age of the patients ranged from 28 to 80 years. Patient demographics including age, gender, height, and body mass index (BMI) are summarized in Table 1.

Table 1 Patients' Demographics of Chest CT Scan for Radiotherapy Treatment Planning.

Statistic	**Age(years)**		**Weight(kg)**		**BMI (kg/m^2)**	
	Male	Female	Male	Female	Male	Female
Minimum	53	28	64	35	21.24	15.55
25th percentile	53.5	43	65	63.5	21.36	24
Median	58.5	47.5	68	70	24.05	26.48
75th percentile	66	57	77.75	75	27.18	28.45
Maximum	80	80	82	105	32.52	40.16

CT dosimetry

In order to obtain the effective dose of sensitive organs in the thoracic region for radiotherapy treatment planning for patients undergoing a chest CT scan, the dosimetic CT parameters including CTDIvol (mGy), DLP (mGy.cm), tube current product (mAs), tube voltage (kVp), slice thickness (mm), scan length(mm), collimation size(mm), and pitch factor, were extracted from CT scan console (Table 2).

Table 2 Dosimetric Data of Chest CT Scan for Radiotherapy Treatment Planning.

Scan parameters	Value
kV	120
Effective mAs	180
Pitch factor	0.938
Slice thickness	2mm
Rotation time	0.5s
Collimation size	16×1.5mm

Dosimetric calculations of CT parameters

$\mathbf{CTDI_{vol}}$, $\mathbf{CTDI_W}$, DLP

$\mathrm{CTDI_{vol}}$ quantity is used to indicate radiation dose for a specific scan protocol, which usually includes a series of scans. It is essential to consider any gaps and/or overlaps between x-ray beams from consecutive rotations of the generated x-ray source. While $\mathrm{CTDI_w}$ refers to the measurement average absorbed radiation dose over two x and y axes at the center of the scan from a series of axial scans where scatter tails are negligible beyond the 100-mm integration limit, CTDIvol indicates the average absorbed radiation dose over three x, y, and z axes.$\mathrm{CTDI_{vol}}$ is calculated Eq. 1 (McNitt-Gray 2002)

$$\mathrm{CTDI_{vol}(mGy)} = \frac{\mathrm{CTDI_W(mGy)}}{\text{Pitch factor}} \quad (1)$$

The product of $\mathrm{CTDI_{vol}}$ and the CT scan length along the Z-axis of the patient, is the DLP. The DLP quantity indicates the total absorbed energy and as a result is the potential biological effect attributable to the complete scan acquisition, calculated by the following Eq. 2:

$$\mathrm{DLP(Gy.cm)} = \mathrm{CTDI_{vol}(mGy)} \times \mathrm{L(cm)} \quad (2)$$

Where L is the scan length.

Radiation Dose Estimation

After obtaining the data set, to estimate the organ dose for each patient, the ImPACT CT patient dosimetry calculator (version 1.0.4) was utilized, and the organ dose was calculated using the Eq. 3:

$$D_{organ} = D^{*}_{organ}\,(70) \times CTDI_{VOL} \qquad (3)$$

Where D^{*}_{organ} is the normalized organ dose for a 70-kg adult, acquired from the ImPACT CT spreadsheet using the Eq. 4:

$$D^{*}_{organ}\,(70) = \frac{D\ organ\ _{Impact}}{CTDI_{Impact}} \qquad (4)$$

and the $CTDI_{vol}$ was extracted from CT scan console.

To estimate the organ dose for each patient with different weights, the Eq. 5 was used:

$$D_{organ}\,(w) = D_{organ}\,(70) \times R(w) \qquad (5)$$

Where, R(w) is the patient weight correction factor.

$$R(W) = 1.73 - 1.33 \times 10^{-2}\ w + 4.04 \times 10^{-5}\ w^{2} \qquad (6)$$

in which W is the patient mass (kg).

The effective dose for a patient of weight (w) was acquired using two methods:

First, using ImPACT CT dosimetry calculation and applying related correction factors according to the patient's weight:

$$E_C\ (mSv) = DLP \times C\text{- Factor} \times R(w) \qquad (7)$$

In which DLP was obtained from the CT scanners console, C-factor is the conversion factor acquired by dividing effective dose by DLP, both of which were acquired from ImPACT software.

Second, the effective dose was determined from the scanner-derived DLP using the below equation:

$$E_D = E_{DLP} \times DLP \quad (8)$$

Where, E_{DLP} is 0.017 $mSv.mGy^{-1}.\ cm^{-1}$, according to Table 3.

Table 3 Normalised Values of Effective Dose per DLP over Various Body Regions (Jessen et al. 2000)

Region of body	**Normalized effective dose,** E_{DLP}
Head	0.0023
Neck	0.0054
Chest	0.017
Abdomen	0.015
Pelvic	0.019

Estimation of cancer risk from radiation

LAR is defined as the probability of radiation-induced cancers in a population of 100,000 who have been exposed to 100 mGy, the equations were obtained from BEIR VII.

$$LAR(D,e) = \frac{\sum_a^{80} M(D,e,a).S(a)}{S(e)} \quad (9)$$

$$M(D,e,a) = ERR(D,e,a)\ .\ \lambda_I^C(a) \quad (10)$$

Where M(D,e,a) is the excess relative risk, D is the radiation dose (Sv), e is the age at the time of exposure in years, a is the attained age in years, S(a) is the probability of survival to age a, S(e) is the probability of survival to age e, $\lambda_I^C(a)$ is the baseline incidence risk for a specific gender and age (National Research Council 2006). LAR can be estimated for a specific cancer or all cancers combined (Salibi et al. 2014; Bagherzadeh et al. 2018)

We estimated cancer risk induction using patient-specific organ dose, gender, and patient's age at the time of exposure. In order to estimate cancer incidence, we used tables 12D-1 in the BEIR VII report, similar to the previous studies (Bagherzadeh et al. 2021; Kritsaneepaiboon et al. 2018; Faletra et al. 2010). The BEIR VII report is retrieved from data collected from the survivors of Hiroshima and Nagasaki (National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation).

Statistical analysis

In this study, statistical software, SPSS version 25, was used to analyze the data. Pearson correlation coefficient test was used to analyze the relationships between quantitative-quantitative variables. We also used the Eta correlation coefficient test to analyze quantitative-qualitative variables. Polynomial regression test was used to examine the relationship between one variable and several other variables. Statistically significant p-value was considered <0.05.

Results

In the present study, the mean and standard deviation of age, weight and BMI were 50.47±11.92 years, 69.33±14.20 kg, 26.12±4.36 kg/m^2 for women and 61±8.76 years, 17.10±6.75 kg, and 25.05±4.11 kg/m^2 for men respectively.

Table 4 represents the radiation dose parameters and the all cancer incidence risk. Mean and standard deviation of DLP, $CTDI_{vol}$ and scan length were 507.5±142.7 (range: 180.8-882.5 mGy.cm), 11.04±3.66 (range: 11.04±3.66 mGy), 46.88±6.65 (range: 26.5-66 cm) respectively.

Table 4 Statistics of Radiation Dose Parameters and All Cancer Risk (ACR)

Statistic	**Minimum**	**25 th percentile**	**Median**	**75 th percentile**	**Maximum**
$CTDI_{Vol}$(mGy)	4.84	9.02	11.93	12.43	24.43
DLP (mGy.cm)	180.8	419.6	512.3	610.35	882.5
Scan length (cm)	26.5	43	46.5	50.5	66
Effective dose(mSv) (E_C)	3.68	8.38	10.35	12.61	15.38
Effective dose(mSv) (E_D)	3.07	7.12	8.70	10.37	15
Male ACR per 100000	21	46.95	54.5	65.25	76
Female ACR per 100000	20	44.86	61	90	160

The CTDI and DLP versus BMI graphs show that as BMI increases, these two values also increase (Figure 1).

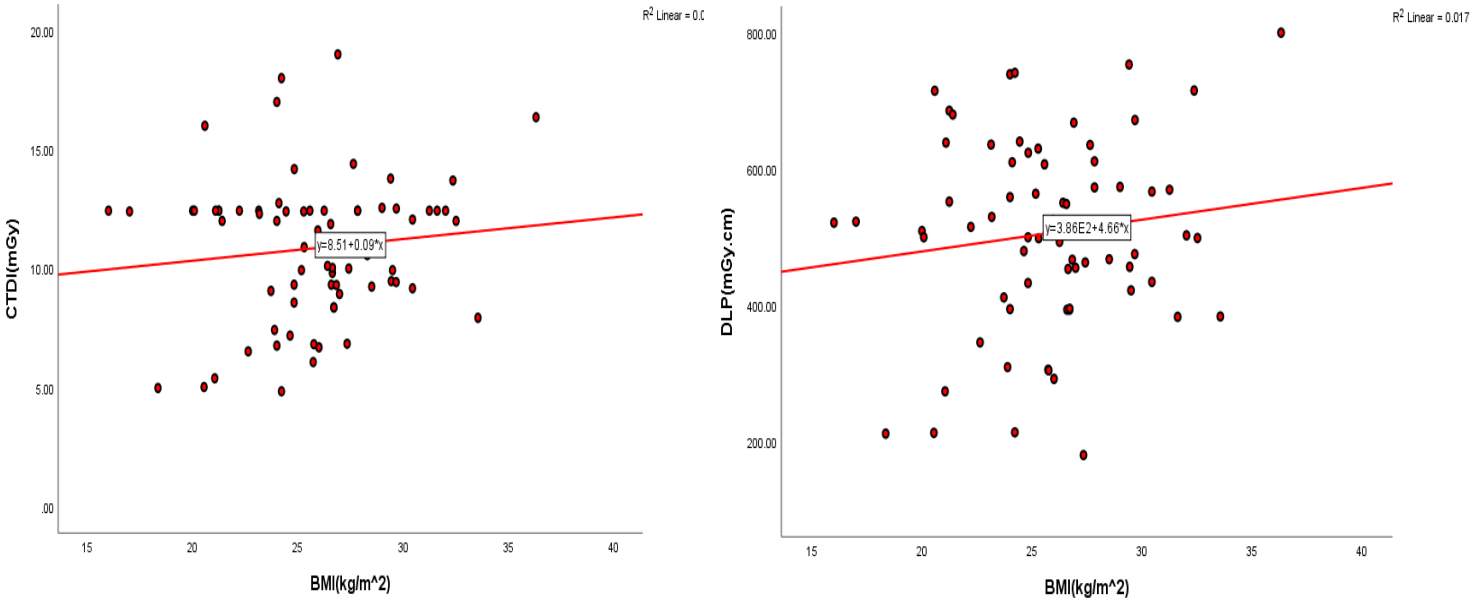

Fig.1 The relationship between CTDI(a), DLP(b) and BMI.

The results showed that the mean effective dose (E_C)was 10.31±2.88 (range of 3.68-15.38 mSv) by means of software and 8.42±2.42 (range of 3.07-15 mSv) using DLP to E conversion factor(E_D). In case of women, the organ that received the maximum absorbed dose was the esophagus with an average of 18.52±6.89 (range of 8.16-40.87 mGy) and then the lung with an average of 17.69±6.43 (range of 7.8-37.47mGy). In case of men, the esophagus was first with a mean of 20.91±1.5 (range of 18.92-21.79 mGy) and the then lung with a mean of 20.03±1.1 (range 18.13-20.88 mGy) (Table 5)

Table 5 Absorbed Doses From Chest Radiotherapy Planning CT Scan.

-	Males		Females	
Organs	**Mean±SD**	**Range**	**Mean±SD**	**Range**
Lung	20.03±1.1	18.13-20.88	17.69±6.43	7.8- 37.47
Stomach	18.49±1.77	15.24 -19.97	14.64 ±4.91	1.14– 23.41
Breast	-	-	14.46 ± 5.43	6.3– 32.36
Liver	17.96± 1.53	15.24 – 19.06	14.7 ± 4.7	1.85 –23.09
Esophagus	20.91±1.15	18.92– 21.79	18.52±6.89	8.16– 40.87
Thyroid	3.29 ± 0.19	2.99– 3.45	2.89±1.09	1.3 – 6.47
Heart	19.87±1.37	17.34– 20.88	17.41±6.38	7.63– 37.47

LAR mean and standard deviation for all cancers, leukemia and all solid cancer were 53.86±15.53, 10.9±1.91, 48.9±18.22 in male patients and 67.43±29.82, 5.9±1.71, 63.85±28.01 in women, respectively, per 100,000 people.

Also, the all cancer risk against BMI shows that with increasing BMI, the risk of all cancer increases (Figure 2a), also the risk all cancer against effective dose shows that with increasing, effective dose the risk of all cancer increases (Figure 2b).

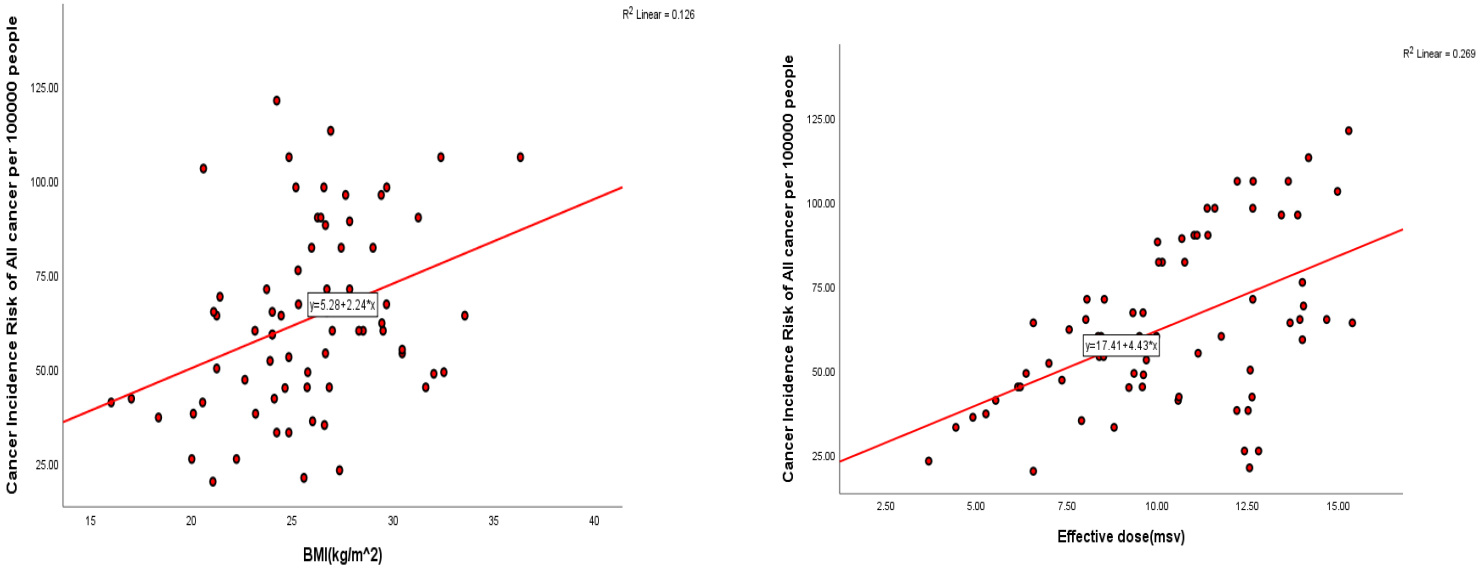

Fig. 2 a) All cancer induction risk against patient's BMI b) All cancer induction risk against effective dose.

In both genders, the highest risk of organ cancer was related to lung, with moderate and standard deviation of 18.4±9.07 in men and 35.68±14.27 in women per 100,000 people. The lowest risk of cancer was related to thyroid cancer (0.03 ± 0.13) and liver (1.26 ± 0.12) in men and women, respectively.

The results also showed, by increasing age, the risk of incidence all solid cancer and all cancer was decrease, but the risk of incidence leukemia was increased (Figure 3).

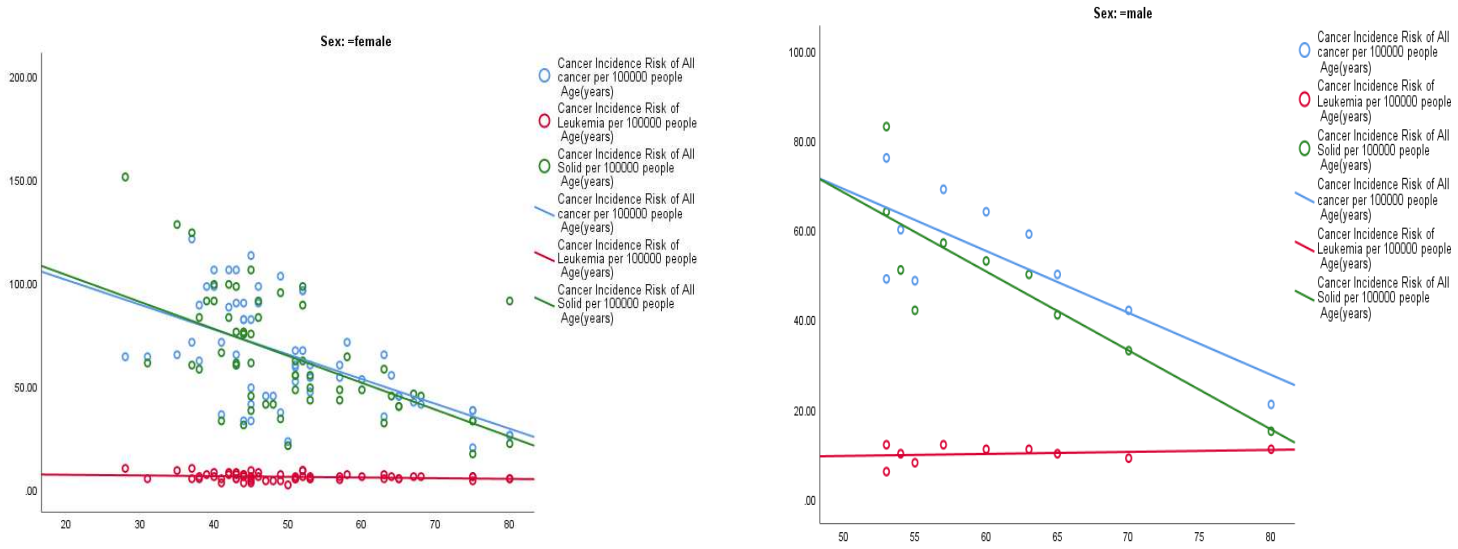

Fig. 3 The all cancer, leukemia , all solid cancer incidence risk against patient's age.

Discussion

Due to the fact that the role of imaging in radiotherapy starts from accurately determining the target volume range and follows up to dosimetry and dose calculation based on radiobiological parameters and tissue characteristics, this study was performed in order to determinate the effective dose and organ dose to estimate the lifetime attributable risk of cancer incidence related to chest CT simulations for radiotherapy treatment planning (RTTP) according to patient-specific information.

The mean of CTDIvol, DLP, and scan length was 11.04 mGy, 507.5 mGy.cm, and 46.88 cm, respectively. These values were lower than the results of the study by Sanderud et al (2015)(CTDIvol =38.1 mGy, DLP = 1472 mGy.cm, and scan length = 38.7 cm). This difference may be attributed to the CT scan parameters and type of scanner used in these two studies.

The mean effective dose was 10.31 mSv using ImPACT patient dosimetry (E_C) and 8.62 mSv using DLP to effective dose conversion factor (E_D), the difference of which may be due to the fact that this factor is equal for all patients and it neglects the BMI of the patients. In addition, the E_D is lower than that of E_C which is in accordance with the study by Mahmoodi and chaparian (2010) Thus, the $E_C$should be considered as the more accurate ones here, due to E_D dose not take into account the patient's characteristics, scan parameters and the type of scanner (McCollough et al. 2010).

The mean effective dose (E_C) in the present study was 10.31 mSv which is lower than that of the study by Albert (2013)for routine chest CT (8 mSv). This difference may be due to the effective dose depending on scan range, slice thickness, tube current, tube voltage, and other machine-specific parameters, the most important of which is tube current, so that a 50% reduction in tube current can reduce the dose by half (Manssor et al. 2015)

According to ICRP publication 87 the diagnostic reference level of DLP (RDLP) is 650 mGy.cm for routine chest CT. The effective dose, which is the product of DLP (650mGy.cm) and DLP to effective dose conversion factor (0.017), is equal 11.05 mSv which has an average value of 8.62 mSv in the present study, being in line with ICRP publications (International Commission on Radiological Protection 2000)

The breast organ dose for female patients ranges from 6.5-32.5 mGy, with an average dose of 14.5 mGy that was in line with Lahham et al. in which the breast organ dose from chest CT scan was 6.5-28 mGy, with an average dose of 15mGy (Lahham et al. 2018)

In this study, there is a direct relationship between BMI and DLP (Figure 1.a)which is in line with the results of study by Mclaughlin et al (2018), since the body tissue volume, especially adipose, affects the amount of radiation dose. Also, there was a direct relationship between BMI and CTDIvol (Figure 1.b), in accordance with the results of study by Bagherzadeh et al (2018), which may due to the fact that the current tube modulation was increased for noise reduction in high BMI patients.

In our study, the mean LAR values in patients undergoing chest CT with a 16-slice Philips scanner was 61.71±27.24 per 100000 individuals for all solid cancers which is almost three times the study by Ghetti et al (21 per 100000 individuals) (2020)These differences are due to use of low dose protocol and decreased organ dose in Ghetti's study, leading to decrease in LAR.

LAR for young female was highest in our study which is in line with the study by Mahmoodi et al (2010), and may be due to the breast being in the radiation range receiving a high dosage and also the proximity of the thyroid to the chest CT which causes high doses.

The highest LAR organ in both genders was related to lung and this value was twice as high in women as in men, which may be due to the greater sensivity of lung to radiation in women. In other words, although the lung organ dosage was lower in women, the lung LAR in women of all ages was twice as high as in men. The LARs of cancer incidence increased with increasing effective dose (Figure 2.b) which is in line with the study by Einstein et al (2008) using a 16-slice scanner in which a strong relationship between these two parameters was found.

The study shows an indirect relationship between LAR and age (Figure3) according to the study by Huda et al (2011). LAR of all cancer for a 20-, 40- and 60-year female was 106, 53 and 26 per 100000 people, respectively. This value for a 60-, 70- and 80-year man was 49, 42 and 21 per 100000 people, respectively.

Also, the results of our study show higher risk for all solid cancer based on the Linear No-Threshold (LNT) model compared to leukemia based on a linear-quadratic model.

Our study of calculation doses and cancer risk estimation has several limitations. First, the BEIR VII data are mostly base on the population with different radiation exposure (atomic bomb, occupational) from our study and regulate for U.S demographic. Second, the radiation-weighting factor (w_R) for diagnostic x-rays is '1 'but for high-energy photons may be twice that the BEIR

VII data are mostly based on high- energy gamma rays, therefore the BEIR VII data estimate risk for x- ray exposures with a factor of two or three times (Kim et al. 2010). Third, due to the high prevalence of breast cancer, our study volume was mainly women.

Conclusion: The cancer risks associated with the radiation doses used for chest tomography simulations for radiotherapy treatment planning (RTTP) are not negligible, and should be considered at the population level. The highest LARs were related to the occurrence of the lung cancer in both genders. LAR is a function of organ dose, thus it is necessary to adjust radiation exposure parameters such as using optimum mAs, reduction of kVp, using optimum scan length in order to reduce future radiation-induced cancer. In addition, due to high LAR cancers from RTTP, medical imaging staff should be familiar with protocol variety to keep radiation dose as low as reasonably achievable.

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