ASSESSMENT OF COMPUTED TOMOGRAPHY SIMULATORS USED IN RADIOTHERAPY TREATMENT PLANNING IN SERBIA, CROATIA, AND BOSNIA AND HERZEGOVINA

by

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The purpose of this work was to evaluate computed tomography simulators used in radiotherapy treatment planning in Serbia, Croatia, and Bosnia and Herzegovina. A survey of quality assurance programmes of 24 computed tomography simulators in 16 facilities was conducted. A dedicated CT-to-ED phantom was scanned at 120 kV and 140 kV, to obtain CT-to-ED conversion curves as well as $CTDI_{vol}$. Thoracal phantoms were scanned in the standard and extended field of view to evaluate the dosimetric effect on treatment planning and delivery. The mean age of the measured scanners was 5.5 years. The mean water HU value was –6.5 (all scanners, all voltages) and air HU value was –997. Extended field of view computed tomography data differ from the standard field of view and differences between conversion curves have significant dosimetric impact. The CTDI data showed a large range of values between centers. Better quality assurance of computed tomography simulators in all countries is recommended. The CT-to-ED curve could be used as default at one voltage and per manufacturer. Extended field of view imaging can be used, but treatment planning should be avoided in the regions out of the standard field of view.

Key words: computed tomography simulator, radiotherapy, conversion curve CT-to-ED, radiotherapy treatment planning, quality assurance

INTRODUCTION

Radiotherapy as it is known today involves extensive use of imaging, and starts with computed tomography (CT) scanning of each patient, followed by image transfer to the treatment planning system and finally transfer of a treatment plan to a linear accelerator for delivery.

In the early days of 3-D conformal therapy (3-D CRT), CT scanners were only available in diagnostic

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departments. The gantry openings of these CT scanners were of the order of 70 cm. As the number of patients increased, and different types of immobilizing devices were introduced into clinical practice, radiotherapy departments began procuring CT scanners – CT simulators dedicated to radiotherapy imaging and specially designed to accommodate immobilizing devices.

This has improved the quality of the treatment planning system (TPS) input data, but also created a new burden for radiotherapy departments, in terms of additional quality assurance tests on CT simulators [1].

At the same time, treatment planning systems were developing fast, and required additional acceptance and performance testing, inclusive of end-to-end testing of the radiotherapy chain. One of the most important issues was conversion of CT data into the data which can be used by TPS. The CT image data set is nowadays exported from the CT simulator and imported into the treatment planning system using the conversion curve of CT numbers to electron density of every material at the CT data set. This is achieved by correlation of material of known electron density and CT number, and interpolating for every other material.

The first motivation for this work was based on the need to enter the conversion curve in the treatment planning system before the first patient is planned. Not many departments in this region have access to the necessary equipment for this purpose. During the planning phase of the study, work was extended from comparison of CT conversion curves of CT devices and dedicated CT simulators produced by available manufacturers, to the behavior of CT conversion curves in the extended field of views and dosimetric impact on treatment planning, patient doses during CT simulation and a short survey on the quality assurance practice in Bosnia and Herzegovina, Croatia and Serbia.

METHODS AND MATERIALS

The examination at each clinic was initiated by running the survey developed for this purpose and was continued with the predefined set of measurements at the available CT scanners.

The survey contained questions about the CT manufacturer, type or model of the scanner, year of installation, information on tube age and if it had been replaced during the lifetime of the scanner. The set of questions on quality assurance briefly evaluated the QC system implemented; type of implemented protocol (choice of institutional, national, International Atomic Energy Agency (IAEA), American Association of Physicist in Medicine (AAPM), and open questions on protocol conducted locally). Daily workload, dedication of the scanner to the radiotherapy (RT) department (used for treatment planning only) or sharing with the diagnostic department; if the scanner has an option on extended field of view and if the reconstruction algorithm is known.

The single dedicated electron density phantom was carried to all clinics to avoid any manufacturing differences. The model chosen for the study was 062M (manufactured by CIRS, USA) previously proven to be a valuable tool for conversion of the CT number to relative electron density. The phantom was scanned using two tube voltages (120 kV and 140 kV), according to the institutional scanning protocol for the abdomen region in radiotherapy departments or in the diagnostic department in cases where the CT scanner is shared between the diagnostic and radiation therapy department.

The scanning was done four times: twice at the standard field of view (sFoV) at two tube voltages and twice at the extended field of view (eFoV) at two tube voltages. In case of scanning in sFoV the phantom was centrally placed on the CT patient couch. In case of eFoV scanning, the image was generated by scanning the phantom shifted laterally 15 cm, so that the CT numbers can be read in the eFoV reconstruction, as shown in fig. 1.

All CT data were read directly from the CT console, in order to avoid any interaction with other radiation therapy software or hardware.

The data taken from the console images were: voltage and current applied, CT numbers, $CTDI_{vol}$ as displayed.

For the purpose of evaluation of treatment planning and delivery dosimetric result in the extended field of CT view, the Intensity Modulated Radiaton Therapy

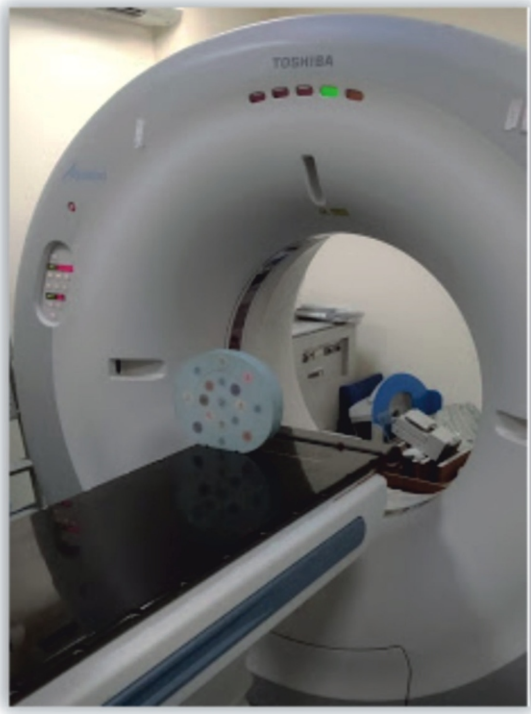

Figure 1. The CT-to-ED phantom setup on a CT patient couch

(IMRT) thorax phantom LFC 002 (manufactured by CIRS) was scanned centrally positioned on a CT patient couch and laterally shifted for 15 cm. The reason behind this was the observed change of geometry and shape when imaged in the extended field of view and possible dosimetric impact when eFoV CT data are applied to an IMRT/VMAT treatment plan. This was achieved by application of the same VMAT treatment plan to:

– CT data of the centrally placed phantom, and
– CT data of the shifted phantom together with the eFoV CT-to-ED conversion curve.

The plans were compared in terms of gamma analysis. This was done for one type of CT scanner (Siemens Somatom Definition AS Open at 140 kV).

RESULTS

Survey results

All CT scanners were installed in public clinical centers, with a high workload.

There were in total 24 CT scanners examined in 16 radiation therapy and diagnostic departments in the Republic of Croatia, Republic of Serbia, and Republic of Bosnia and Herzegovina. CT scanners were manufactured by Siemens (12), General Electric (7), Toshiba (3) and Philips (2). The mean age of equipment was 5.5 years (newest one 2 years and oldest 13 years old at the time of this investigation). The X-ray tube was replaced in half of the CT scanners during their clinical life, after the sixth year of exploitation on average. The tab. 1 bellow gives an indication of the age distribution and tube replacements.

Over all departments, thirteen CT scanners were used for radiotherapy only, while six were shared between the diagnostic and radiotherapy department. Five scanners belong to diagnostic departments and were used for diagnostic purposes only, serving as backup scanners in case the radiotherapy scanner failed. The gantry openings in the radiotherapy scanners were 80 cm or 90 cm. The shared CT scanners had a gantry opening size 70 cm or 80 cm, while for the diagnostics only CT scanners had a 70 cm gantry opening size.

The average number of imaged patients was 10 per day for radiotherapy scanners, while in cases where the scanner was used for both diagnostics and radiotherapy, 23 patients were scanned daily, if it was used solely as a diagnostic CT scanner, 31 patients were scanned daily.

All three countries have regulated on the national level the minimum quality assurance test of CT scanners in medical use of ionizing radiation. The survey was conducted to evaluate to which extent these regulations were followed. In case of implementation of additional tests, the applied protocol was noted, as well as the frequency of testing the device and its performance.

Out of 24 users, 16 users claimed to perform quality assurance testing once per year as required by national law [2-4]. The details on testing could be found in literature [2-4]. One user has implemented Quality Assurance (QA) tests as recommended by the American Association of Physicists in Medicine (AAMP). The International Atomic Energy Agency recommended QA tests [1] were implemented in 5 radiotherapy departments, while the remaining 2 users follow the manufacturer defined protocol only.

Distribution of QA tests is given in tab. 2.

Measurement results

In total four CT-to-ED curves per CT scanner for the CIRS 062M phantom were generated: two curves at tube voltages which were most often used for CT imaging 120 kV and 140 kV, and two curves at the same voltages but shifted from the isocenter laterally when the extended field of view function was employed. Both phantoms CIRS 062M as well as CIRS LFC002 were scanned in the clinically used abdominal scanning protocol where the tube current was predefined.

The CT number in the standard field of view

Across all voltages and devices, the mean water HU value was –6.5, ranging –13 to 0 and the mean air HU value was –997 (–1024 to –976). The tab. 3 shows minimum, maximum and mean values per manufacturer and per voltage applied.

The following graphs show a set of 12 CT-to-ED curves at Siemens CT scanners, across two voltages as shown on figs. 2(a) and 2(b).

Table 1. Age of equipment and tube replacements

Age of equipment (year)	0-2	3-5	6-8	9-11
Total number of CT scanners	8	4	6	6
Original tube	8	3	2	1
Tube replacement	0	1	4	5

Table 2. The QA tests and frequency

	Total number	Manufacturer protocol	National protocol	IAEA recommended	AAPM recommended
Daily	8	6	0	2	0
Weekly	5	3	0	1	1
Monthly	10	8	0	2	0
Annually	22	6	16	0	0

Table 3. Minimum, maximum and mean values of CT numbers per manufacturer and tube voltage, for each tissue insert in the phantom

Insert	Tube voltage [kV]	Siemens			General electric			Toshiba			Philips		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Water	120	–13	–6	–9	–9	0	–5	–10	–8	–9	–9	0	–4
	140	–12	–1	–7	–7	0	–4	–10	–3	–7	–6	–6	–6
Air	120	–	–997	–	–997	–981	–990	–	–	–	–	–	–
		1024		1003				1007	1001	1004	1004	1002	1003
	140	–	–998	–	–996	–976	–988	–	–999	–	–999	–999	–999
		1003		1000				1006		1002			
Adipose	120	-66	–54	–61	–61	–48	–55	–64	–55	–61	–74	–64	–67
	140	–63	–49	–57	–56	–45	–52	–59	–50	–55	–58	–56	–57
Lungs inhale	120	–794	–773	–784	–779	–753	–766	–812	–785	–794	–799	–788	–794
	140	–793	–774	–784	–777	–753	–765	–838	–783	–802	–790	–790	–790
Lungs exhale	120	–501	–484	–492	–490	–471	–479	–532	–488	–503	–511	–494	–500
	140	–505	–484	–493	–489	–471	–480	–576	–487	–518	–497	–496	–496
Liver	120	35	56	46	47	73	57	38	58	52	35	49	44
	140	35	56	46	48	67	56	37	59	52	47	54	50
Muscles	120	36	51	44	44	69	54	42	58	50	38	47	44
	140	32	53	45	45	64	52	41	60	50	48	52	50
Breast	120	–47	–25	–34	–35	–14	–24	–39	–26	–31	–41	–31	–36
	140	–40	–21	–31	–31	–14	–22	–32	–23	–28	–33	–25	–29
Bone 200	120	199	246	216	213	245	231	218	255	237	213	229	220
	140	172	202	196	198	221	210	187	238	215	200	214	207
Bone 800	120	786	939	838	860	919	880	903	1122	981	858	869	866
	140	720	770	756	776	818	795	833	1272	985	790	795	793
Bone 1250	120	1219	1417	1270	1291	1363	1314	1366	1709	1483	1304	1317	1310
	140	1105	1172	1147	1168	1218	1189	1259	1900	1477	1197	1197	1197

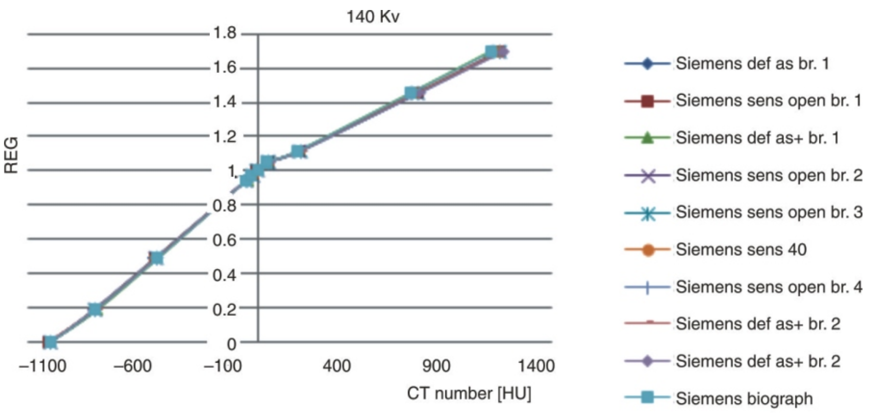

Figure 2(a). The CT-to-ED conversion curves at 12 Siemens CT scanners, at tube voltage 140 kV

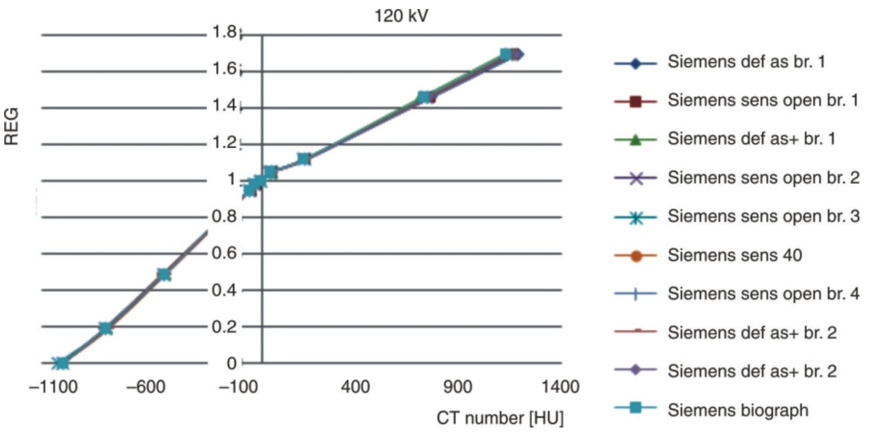

Figure 2(b). The CT-to-ED conversion curves at 12 Siemens CT scanners, at tube voltage 120 kV

The CT numbers in the extended field of view

In a number of clinical cases, in patients with a higher body mass index (BMI) or when positioning devices requiring extension of field of view are used, such as the pronatory breast board, a part of the patient's body is visible out of the sFoV of 500 mm (figs. 3 and 4). The inaccurate patient data outside sFoV lead to inaccurate reconstruction of the image and reduced accuracy of CT numbers in the extended FoV region of 650 mm leading to inaccurate dose calculation and delivery, which may go up to 20 % [5]. To overcome the problem, manufacturers have developed extended FoV algorithms to increase the accuracy of reconstruction outside the standard FoV [6, 7].

When the phantom was shifted laterally 15cm on the patient couch, so that the extended field of view for imaging must be included, fig. 3, the conversion curve generated changes and exhibited a lower CT number, thus underestimating the CT numbers, and it applies throughout all CT examined at all voltages.

The greatest difference is registered in higher density materials such as bones, and least for air and lungs. An example is given in tab. 4.

The eFoV algorithm estimates CT data in regions which were not covered during the measurements, using the principle of mass conservation in projection data [5]. Since this is true for 2-D data acquisition in fan or parallel beam geometry, when CT scanners have a cone beam geometry and use the 3-D spiral scan mode, this principle is violated and is only

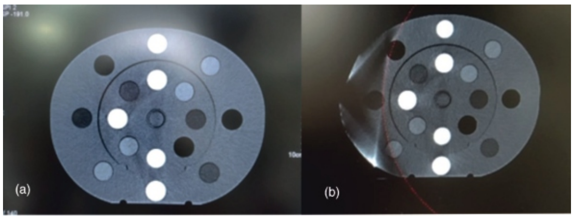

Figure 3. The CT-to-ED conversion phantom placed centrally to standard FoV (a) and moved laterally with extended FoV (b)

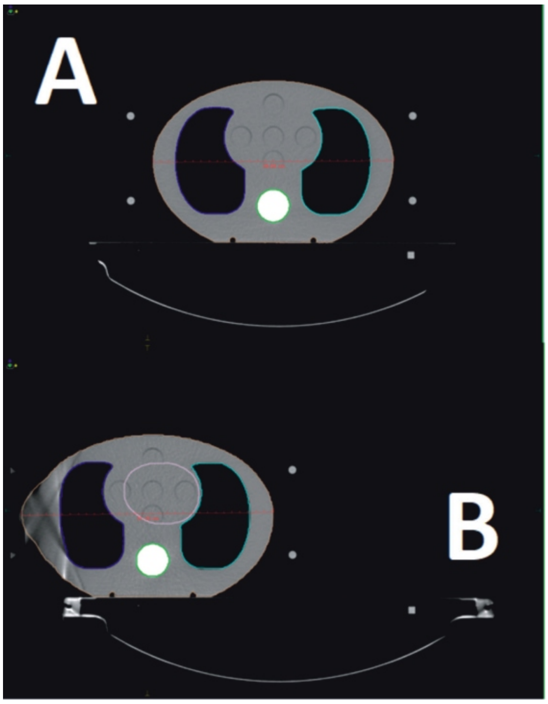

Figure 4(a) and (b). The IMRT phantom CT imaged centrally and shifted laterally 15 cm on a CT patient couch

approximately true. This is a known limitation of the extended field of view reconstruction algorithm in the Siemens CT scanner. Similar applies to other manufacturers [5, 8, 9].

On the other hand, reconstruction starts from the estimate of the patient boundary from the limited data. The Siemens reconstruction in the extended field of view assumes that every projection that covers the entire object has constant mass. If an object extends beyond the standard field of view, this condition is violated and projections are truncated during measurements. Projection mass is assumed to be the normalized cumulative sum of attenuation values as a function of the full arc and is 1 if the whole object is seen. Artefacts may appear if the transition between measured and extrapolated data is not smooth. Some manufacturers achieve a reconstructed image in eFoV through correctional algorithms based on

Table 4. Standard (sFoV) and extended (eFoV) CT numbers, GE Discovery RT590

Tissue type	Relative electron density (RED)	The CT number 120 kV		The CT number 140 kV	
		Standard FOV	Extended FOV	Standard FOV	Extended FOV
Air	0.001	–1024	–1006	–999	–1002
Lung inhale	0.19	–782	–769	–780	–774
Lungs exaleexhale	0.489	–490	–462	–491	–439
Adipose	0.949	–62	–49	–57	–17
Breast	0.976	–35	–54	–30	–42
Water	1	–11	–16	–8	–12
Muscles	1.043	43	8	45	18
Liver	1.052	46	17	48	50
Bone 200	1.117	216	192	202	182
Bone 800	1.456	827	768	762	710
Bone 1250	1.695	1260	1123	1154	1037

extrapolation of the partial data set acquired within the conventional sFoV [5].

This extended field of view limitations in terms of different CT number and phantom distortion, may be significant in cases where the imaged and treated area is far from the central axis of the scanner, such as breast lesions, extremities or peripheral abdominal lesions, which are close to the standard field of view edge or are entering the extended field of view [5, 7, 10]

The measured CT-to-ED curve in sFoV and eFoV is shown on fig. 5. as applied in case of the Siemens Sensation Open. Similar findings apply to all scanners examined as shown in fig. 6.

Another issue has been observed: geometrical distortion of the patient image in the extended field of view, followed by a change of Source-to-Skin Distance (SSD) [10]. This was tested by the thorax phantom of a precisely know size. The reconstruction in the extended field of view gave a difference as in tab. 5.

To estimate the possible dosimetric impact, a test VMAT plan was calculated on a centrally located thorax phantom, which was then applied to the CT dataset of the phantom which was moved laterally. The plan was analyzed by 4-D Octavius (PTW, Germany), containing 1500 detectors and 3-D gamma analysis compared between the central and shifted planned CT data set.

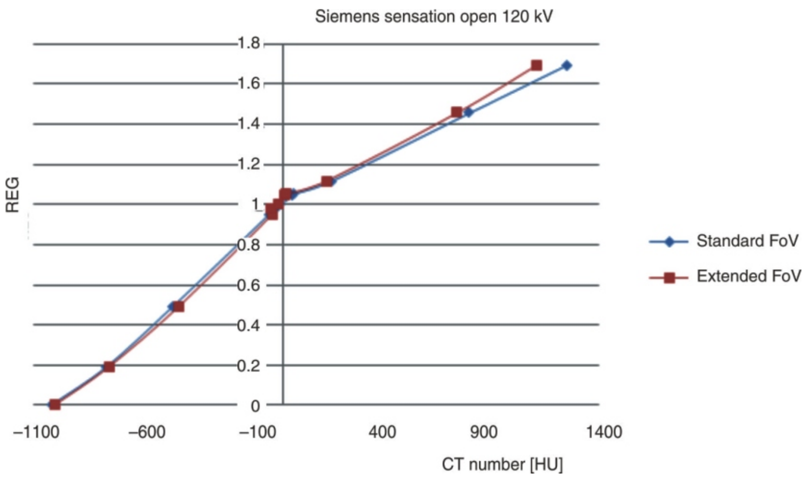

Figure 5. The CT-to-ED curve in case of the Siemens CT scanner in sFoV and eFoV

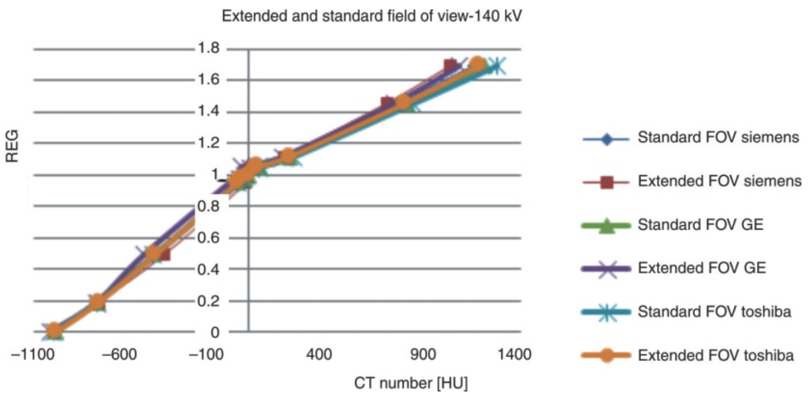

Figure 6(a). Averaged CT-to-ED conversion curves at the standard and extended field of view at 140 kV

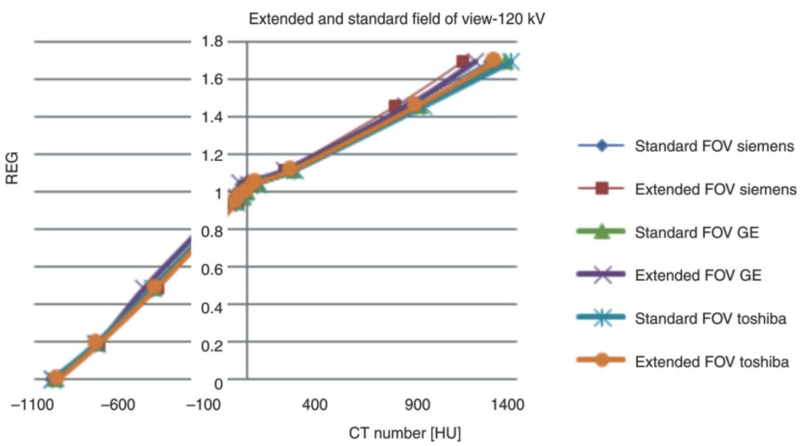

Figure 6(b). Averaged CT-to-ED conversion curves at the standard and extended field of view at 120 kV

Table 5. Influence of eFoV on dosimetric and geometric evaluation of patient data

	Standard FoV scan	Extended FoV scan	Difference [%]
Phantom diameter measured physically [cm] – lateral dimension	30.0	31.18	3.9
Phantom volume measured by external body contour [cm^3]	14662.35	14961.46	2.0
3-D global gamma, 5 % threshold	(1 %, 1 mm): 94.4 %; (2 %, 2 mm) 97.1 %; (3 %, 3 mm): 98.6 %		
3-D local gamma, 5 % threshold	(1 %, 1 mm): 86.7 %; (2 %, 2 mm) 95.2 %; (3 %, 3 mm): 97.1 %		

The phantom distortion has changed the calculation due to the wrong shape of the CT-to-ED data in TPS, and may significantly contribute to failure of the verification plan as well as dosimetric failure to a real patient.

All eFoV significantly underestimated the CT numbers. This is more pronounced at higher voltages and higher densities, when identical scans of tissues are scanned in the central (within sFoV) and shifted (within eFoV) position.

Treatment plan verification in the extended field of view – clinical example

A VMAT treatment plan generated on a CT data set of the centrally placed thorax phantom and the same generated of the same phantom imaged in the extended field of view were compared in terms of gamma value, tab. 5. The tumor to be irradiated was located close to the spinal cord, in the right lung. Its size was 4 cm 5 cm 5 cm. The treatment plan generated exhibited the standard VMAT plan, 360° rotation, 1 full arc. An anthropomorphic thorax phantom was used as a patient.

The fig. 7 shows dosimetric points of failure.

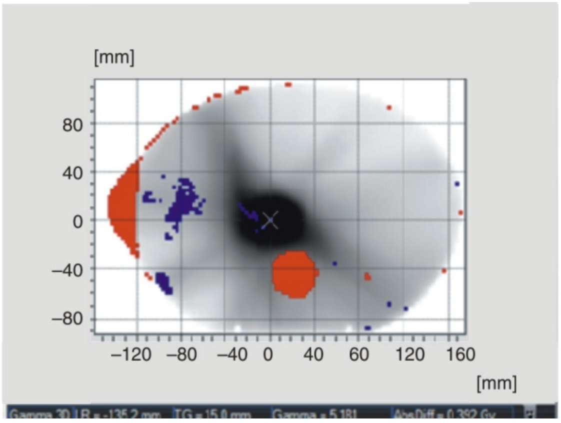

Figure 7. Points of failure in the thorax region of the distorted image and in high density tissue (spine) for the global gamma 1 % dose difference, 1 mm DTA, dose threshold 5 %

The $CTDI_{vol}$

After each scanning of a phantom, according to the clinical protocol, $CTDI_{vol}$ was recorded and compared between manufacturers and countries. The results are given in a tab. 6.

DISCUSSIONS

The survey results, which was conducted in three countries, does not show any significance in terms of distribution or test frequency of implemented QC protocols, meaning all hospitals have fulfilled the minimum regulatory-required testing, and additional internationally recommended tests are locally implemented, based on available equipment and knowledge of local medical physicists. The necessity of implementation of a more detailed QC has been proven.

The CT-to-ED curves measured in the standard FoV of a single manufacturer at a single voltage corresponded very well, so we conclude that the unique CT-to-ED curve can be used as default, in case where the equipment for measurement is not available.

Extended field of view CT-to-ED conversion curves were measured and compared to standard CT-to-ED curves and significant underestimation of CT numbers was observed in the eFoV data set. This emphasizes the importance of evaluation of regions outside the central part, especially for treatment planning purposes of patients with a higher BMI or using immobilizing devices.

The results of the CT-to-ED conversion curve in the extended field of view impact on treatment planning and delivery is confirmed in literature [7-12], and further dosimetric evaluation of the treatment plan at in this region was conducted in this study. The dosimetric impact depends on the technique and location of the tumor in relation to FoV. We have evaluated a VMAT treatment plan as a phantom was placed centrally and shifted, and as expected, a gamma analysis revealed significant difference in the region of high density (spine), and region of distorted image, leading to dosimetric failure of a plan comparison, as proven in literature [7-12]. As a conclusion, better reconstruction algorithms from manufacturers are needed in future applications of eFoV.

The allowed difference in CT numbers should not be larger than 20 HU for the all tissue types, except for water (5 HU) as shown in IAEA guidelines [1], but this condition was violated in all measured points.

The treatment planning should be avoided in the region of eFoV and the planner should try to keep the patient as centrally located as possible. The effect of

Table 6. The $CTDI_{vol}$ for all clinics, given by country

Country 1	Model	Tube voltage	$CTDI_{vol}$ [mGy]	Parameter value	Parameter
Siemens CT	Somatom Def AS 1	120 kV	33.4	250	Quality reference mAs
		140 kV	33.44	173	
	Somatom sensation open	120 kV	7.47	190	
		140 kV	10.57	190	
	Somatom Def AS 2	120 kV	7.88	250	
		140 kV	11.28	183	
	PET/CT Biograph	120 kV	7.27	100	
		140 kV	11.54	100	
GE	Discovery 590RT 1	120 kV	44.81	12.6	Noise index
		140 kV	51.94	12.6	
	Discovery 590RT 2	120 kV	37.58	15.8	
	Discovery 590RT 3	120 kV	44.55	15.8	
		140 kV	51.79	15.8	
	Discovery 590RT 4	120 kV	35.73	11.2	
		140 kV	47.74	11.2	
Philips	Ingenuity CT	120 kV	21.5	364	mAs/slice
		140 kV	22.8	243	
	Mean value	120 kV	26.7		
		140 kV	30.1		

Country 2	Model	Tube voltage	$CTDI_{vol}$ [mGy]	Parameter value	Parameter
GE	Discovery RT16 br. 1	120 kV	33.86	15.8	Noise index
		140 kV	43.94	15.8	
	Discovery VCT 64	120 kV	26.4	15.5	
		140 kV	33.8	14.4	
	Discovery RT16 br. 2	120 kV	44.55	20	
		140 kV	51.79	20	
	Mean value	120 kV	34.9		
		140 kV	43.2		

Country 3	Model	Tube voltage	$CTDI_{vol}$ [mGy]	Parameter value	Parameter
Siemens CT	Somatom Def AS+ 1	120 kV	7.87	210	Quality reference mAs
		140 kV	10.04	169	
	Somatom sensation open 2	120 kV	11.72	190	
		140 kV	15.58	190	
	Somatom sensation open 3	120 kV	7.62	170	
		140 kV	10.79	190	
	Somatom sensation 40	120 kV	6.87	160	
		140 kV	9.57	160	
	Somatom sensation open 4	120 kV	5.45	190	
		140 kV	8.24	190	
	Somatom perspective	120 kV	5.21	125	
		140 kV	7.13	125	
	Somatom Def AS+ 2	120 kV	9.45	210	
		140 kV	11.58	169	
Toshiba	Aquilion LB	120 kV	33.2	10	SD
		140 kV	38.1	10	
	Aquilion LB	120 kV	18.8	10	
		140 kV	26	10	
	Aquilion LB	120 kV	8	12.5	
		140 kV	12.4	12.5	
	Average value	120 kV	11.42		
		140 kV	14.94		

deformation in the extended field of view was discussed by Wu *et al*., [10] as applied to breast treatment plans, where many discrepancies were detected, including the CT number and dose distribution. Our study showed similar sensitivity of the complex VMAT treatment plan to deviations generated by the distorted CT data set in FoV. The dose reports generated showed a large range of $CTDI_{vol}$ between facilities, which indicates the need for optimisation of protocols in CT imaging.

CONCLUSIONS

The CT-ED conversion curves of CT scanners of the same manufacturer and tube voltage are very similar and can be used as default per voltage and manufacturer, in case a curve cannot be measured in a limited resources environment.

Patient scanning protocols should be better optimized to avoid an increase of dose to the patient.

Better understanding of the CT quality control system in radiotherapy departments should be employed in the region and improved in all departments.

Extended field of view images should be reviewed for geometrical distortion and dosimetric impact to the eFoV region and should be avoided in treatment planning.

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ЕВАЛУАЦИЈА СТ СИМУЛАТОРА КОЈИ СЕ КОРИСТЕ У РАДИОТЕРАПИЈИ У СРБИЈИ, ХРВАТСКОЈ И БОСНИ И ХЕРЦЕГОВИНИ

У овом раду евалуирају се особине СТ симулатора које су од значаја при планирању радиотерапије у Србији, Хрватској и Босни и Херцеговини. Упитник о контроли квалитета попуњен је у 16 клиника, за 24 СТ симулатора конверзиони фантом CT-ED скениран је на два напона цеви (120 kV и 140 kV) према институционалном протоколу за регију абдомена, да би се добила CT-ED конверзиона крива као и $CTDI_{vol}$. CT-ED и антропоморфни торакални фантом скенирани су у стандардној и проширеној слици да би се евалуирао дозиметријски ефекат на планирање и испоруку дозе. У просеку старост скенера је 5.5 година. Средња вредност СТ броја је за воду –6.5 (сви скенери и сви напони) а за ваздух –997. Снимање у проширеној и стандардној слици се разликује значајно и има дозиметријски утицај на планирање терапије. $CTDI_{vol}$ указује на значајне разлике између центара у три државе.

У свим државама потребна је боља контрола квалитета СТ симулатора. Крива CT-ED може да се користи као стандардизована за један напон и једног произвођача. Проширено поље може да се користи, али планирање у региону ван стандардне слике треба избегавати.

Кључне речи: СТ симулатор, радиотерапија, конверзиона крива СТ-у-ED, планирање радиотерапије, осигурање квалитета