Received:
21 April 2020

Revised:
12 August 2020

Accepted:
13 August 2020

<https://doi.org/10.1259/bjr.20200412>

Cite this article as:

Piliero MA, Casiraghi M, Bosetti DG, Cima S, Deantonio L, Leva S, et al. Patient-based low dose cone beam CT acquisition settings for prostate image-guided radiotherapy treatments on a Varian TrueBeam linear accelerator. *Br J Radiol* 2020; **93**: 20200412.

FULL PAPER

Patient-based low dose cone beam CT acquisition settings for prostate image-guided radiotherapy treatments on a Varian TrueBeam linear accelerator

¹MARIA ANTONIETTA PILIERO, MSc, PhD, ¹MARGHERITA CASIRAGHI, MSc, PhD, ²DAVIDE GIOVANNI BOSETTI, MD, ²SIMONA CIMA, MD, ²LETIZIA DEANTONIO, MD, ²STEFANO LEVA, BSc, ²FRANCESCO MARTUCCI, MD, ²MARINO TETTAMANTI, BSc, ¹FRANCESCO PUPILLO, MSc, ¹LUCA BELLESI, MSc, ²ANTONELLA RICHETTI, MD and ¹STEFANO PRESILLA, MSc

¹Medical Physics Division, Imaging Institute of Southern Switzerland, Ente Ospedaliero Cantonale, 6500 Bellinzona, Switzerland

²Radiation Oncology Clinic, Oncology Institute of Southern Switzerland, 6500 Bellinzona, Switzerland

Address correspondence to: Ms Maria Antonietta Piliero

E-mail: mariaantonietta.piliero@eoc.ch

Objective: To evaluate the performance of low dose cone beam CT (CBCT) acquisition protocols for image-guided radiotherapy of prostate cancer.

Methods: CBCT images of patients undergoing prostate cancer radiotherapy were acquired with the settings currently used in our department and two low dose settings at 50% and 63% lower exposure. Four experienced radiation oncologists and two radiation therapy technologists graded the images on five image quality characteristics. The scores were analysed through Visual Grading Regression, using the acquisition settings and the patient size as covariates.

Results: The low dose acquisition settings have no impact on the image quality for patients with body profile length at hip level below 100 cm.

Conclusions: A reduction of about 60% of the dose is feasible for patients with size below 100 cm. The visibility of low contrast features can be compromised if using the low dose acquisition settings for patients with hip size above 100 cm.

Advances in knowledge: Low dose CBCT acquisition protocols for the pelvis, based on subjective evaluation of patient images.

INTRODUCTION

The integration of kV imaging devices into linear accelerators has led to a rapid increase of image-guided radiotherapy (IGRT) procedures, improving precision and accuracy of treatment delivery.^{1–3} The drawback of IGRT is the additional imaging dose delivered to both treated volume and surrounding healthy tissues. Organ doses range from tens of mGy to a few cGy, depending on the beam energy (kV or MV) and technique (two-dimensional imaging or volumetric imaging). Compared to the treatment dose, the additional imaging dose is similar to the peripheral dose due to leakage and scattered radiation of more modern treatment techniques, such as intensity-modulated radiation therapy (IMRT) vs three-dimensional-conformal radiotherapy.^{4–6} Studies on radiation exposure from image guidance procedures with cone beam CT (CBCT) in the pelvis area show that organ doses can be up to 5 cGy for bladder, or about 1.5 cGy for the gonads and intestine for each CBCT scan.^{7,8} If IGRT is performed on a daily basis, patients undergo extra additional dose that need to be taken into account.

Strategies to reduce the radiation dose include focusing the radiation field to the area of interest or decrease the exposure settings. Also, partial arc CBCT scans can be used to avoid the beam entrance through critical organs, thus decreasing the organ dose.^{9–11} However, image quality is a crucial issue for treatment verification. In this regard, international guidelines on the management of IGRT procedures suggest the optimisation of the imaging procedures in terms of technique (two-dimensional vs volumetric), frequency and acquisitions settings, in order to fulfil the ALARA (As Low As Reasonable Achievable) principle that is at the basis of the radiation protection.^{12–14}

The optimisation of the imaging procedures is a difficult task since it is a balance between the radiation dose and the image quality, ideally tailored to a specific clinical task. Furthermore, both the image quality and radiation dose depend on the patient size,¹⁵ so the optimised acquisition protocols should ideally be patient specific.¹⁶

Optimisation procedures of CBCT acquisition settings for the pelvis area have already been carried out on phantoms; however, the results depend greatly on the image quality metric considered. Young et al¹⁷ studied the contrast-to-noise ratio (CNR) variability in images of phantoms with increasing diameter and suggested the use of low dose acquisition protocols for paediatric or adolescents patients. On the contrary, Wood et al¹⁸ evaluated the noise variability in the CT AEC phantom (Leeds Test Objects, Boroughbridge, UK) and found that low dose acquisition protocols can be applied to the majority of their patients population. In addition to the dependence on the image quality metric, optimisation studies carried out on phantoms do not take into account the patient variability in terms of body shape and composition.

The aim of the present study was to evaluate the performance of two low dose acquisition settings for the CBCT of the pelvis based on subjective evaluations of patient images, taking into account both the clinical task and the patient variability.

The CBCT images were acquired with the Imaging system of a Varian TrueBeam linear accelerator (v. 2.7 MR3, Varian Medical Systems, Palo Alto CA). Starting from our standard acquisition settings, two low dose protocols were defined by decreasing the exposure settings by 50% and 63%. CBCT images of patients undergoing radiotherapy treatment of prostate cancer were acquired with the standard and the low dose settings. Four experienced radiation oncologists and two radiation therapy technologists evaluated the image quality on five image characteristics using a 4-point grading scale. The results of the subjective evaluations were analysed through the visual grading regression (VGR) method proposed by Smedby & Fredrikson.¹⁹

A standard statistical method for the analysis of visual grading studies has not been defined yet. As a first approach, the grading scale can be converted into numerical values and the results of the image evaluations can be summarised into the so-called Visual Grading Analysis Score, that is the mean value of the scores among the raters and the images. The difference between

different acquisition modalities is assessed through the analysis of variance. However, this approach has been considered inappropriate because ordinal data do not have the same mathematical properties of interval data.²⁰ To overcome this issue, Båth & Månsson²¹ suggested a novel method called Visual Grading Characteristic (VGC) analysis. In VGC analysis, the grading scores are summarised into a $2 \times n$ frequency table showing the number of images scored in each grading level for two imaging modalities (n is the number of the grading levels). For each grading level, the number of images scored up to that level is calculated for the two imaging modalities. The values calculated for the two imaging modalities are plotted against each other, producing a VGC curve. The area under the curve (AUC) is then used to evaluate the difference between the two modalities as it is done in the receiver operating characteristics (ROC) analysis: AUC = 0.5 means no difference between the two imaging modalities; AUC < 0.5 means that the first modality is superior to the second; AUC > 0.5 means that the second modality is superior to the first. The limitation of the VGC analysis is that it does not allow the comparison of imaging modalities involving several independent variables. In this study the aim was to evaluate the image quality for three acquisition settings (STD, Low1 and Low2) at different patient size, therefore there were two independent variables: acquisition settings and patient size.

The VGR analysis is a new method proposed by Smedby & Fredrikson¹⁹ that allows the study of the correlation between the image quality scores and one or more covariates through ordinal logistic regression models. Indeed, VGR analysis has been already used to investigate the effect on the image quality of X-ray tube settings and reconstruction protocols at the same time.^{22,23} Moreover, the intrinsic variability of the patients and of the raters can also be taken into account by using mixed-effects logistic regression models.²⁴

In this work, a binary mixed-effects logistic regression model was used to check the dependence of the image quality on the acquisition settings and patient size.

Figure 1. Distribution of the patient size calculated as the body profile length in the axial slice above the femoral heads of the planning CT scan.

Table 1. Description of the CBCT acquisition settings

	STD	Low1	Low2
Voltage (kVp)	125	125	125
Tube current (mA)	30	30	30
Pulse duration (ms)	20	10	10
Fan type	Half fan	Half fan	Half fan
Scan arc (degrees)	360	360	360
Number of projections	900	900	660
Exposure (mAs)	540	270	198
Frame rate (fps)	15	15	11
Scan duration (s)	60	60	60
Weighted CT dose index (mGy)	8	4	2.9
Pixel matrix	512 × 512	512 × 512	512 × 512
Field of view diameter (cm)	46	46	46
Reconstruction length (cm)	15.5	15.5	15.5
Slice thickness (mm)	3	3	3
Reconstruction filter	Smooth	Smooth	Smooth
Ring suppression	Medium	Medium	Medium

CBCT, cone beam CT.

STD refers to the acquisition settings currently used in our department for the pelvis area; Low1 and Low2 refer to the low dose acquisition settings evaluated in this work.

METHODS AND MATERIALS

Patients selection

Twenty-four consecutive patients undergoing radiotherapy for prostate cancer were selected for this study.

A planning CT scan was acquired for each patient with a Philips Brilliance CT Big Bore in helical mode, 3 mm slice thickness, 120 kVp tube voltage, tube current with automatic exposure control and iDose image reconstruction algorithm (Philips Healthcare).

All patients were treated by volumetric modulated arc therapy (VMAT) technique, with 6 MV photon beam. Radiotherapy dose prescription was 78 Gy in 39 fractions to the prostate gland and seminal vesicles with/without a prophylactic dose of 50 Gy in 25 fractions to pelvic lymph nodes, according to risk stratification. Before starting the radiotherapy treatment, all the patients were instructed on the dietary protocol aiming at empty rectum and full bladder before radiotherapy session.

At present, the IGRT protocol applied to prostate cancer patients in our department requires the acquisition of a daily CBCT for the first three treatment fractions, followed by weekly CBCT acquisitions. An offline review of the CBCT images is performed by the radiation oncologists who check for the reproducibility of the patient positioning and proper bladder and rectum filling. A permanent shift is applied in case of more than 5 mm position displacement.

Two low dose acquisition settings were studied in this work. The details are given in the Data acquisition section. All the patients were scanned with the default acquisition settings currently used in our department and the first low dose settings. Nineteen patients were scanned with the second low dose settings. Five patients were not scanned with the second low dose settings because the CBCT scan with the first low dose settings showed a much worse overall image quality compared to the planning CT. The check of bladder and rectum filling and the check of the patient positioning could still be performed but a further decrease of image quality could have led to a useless image. All five patients were of large size (larger than 110 cm). The patient size was estimated as the body profile length in the axial slice of the planning CT scan above the femoral heads. Clinically, they could be classified as obese.^{25,26}

The distribution of the body profile length of the patient population is shown in [Figure 1](#).

Data acquisition

The CBCT images were acquired with the Imaging system of a Varian TrueBeam linear accelerator, version 2.7 MR3. The CBCT acquisition settings suggested by the manufacturer for the pelvis area are two: Pelvis and Spotlight. The Pelvis protocol include a full rotation of the X-ray source around the patient, 125 kVp tube voltage and 1080 mAs exposure. The diameter of the field of view is 45 cm while the reconstruction length is 15.5 cm. The Spotlight settings include 125 kVp tube voltage, 750 mAs exposure and 200 degrees gantry rotation. The field of view is reduced to 26 cm

Table 2. AC score for the evaluation of the intrarater agreement

Item	Protocol	Rater					
		1	2	3	4	5	6
Visibility of low contrast features							
	STD	0.98	0.83	0.74	0.98	0.89	0.91
	Low1	0.96	0.88	0.78	0.96	0.78	0.80
	Low2	1	0.95	0.85	0.98	0.92	0.98
Visibility of high contrast features	STD	1	0.95	0.90	0.95	1	0.98
	Low1	0.95	0.88	0.85	0.93	0.92	0.98
	Low2	1	1	0.89	1	1	1
Evaluation of bladder and rectum filling	STD	1	0.83	0.82	0.91	1	1
	Low1	0.96	0.88	0.87	0.93	0.92	0.83
	Low2	1	0.92	0.89	1	0.99	0.98
Perceived noise level	STD	0.95	0.71	0.74	0.87	0.88	0.87
	Low1	0.93	0.71	0.88	0.93	0.84	0.77
	Low2	0.98	0.94	0.91	0.95	0.93	0.94
Overall image quality	STD	1	0.77	0.80	0.95	0.89	0.90
	Low1	0.98	0.84	0.77	0.93	0.77	0.84
	Low2	1	0.93	0.95	0.97	0.92	0.94

Values between 0.6 and 0.9 indicate Moderate to Strong agreement. Values above 0.9 indicate Almost perfect agreement.

diameter. The larger field of view is not allowed for partial arc scans.²⁷ The larger field of view is preferred in our department, therefore, the acquisition settings currently used in our department comprise a full rotation of the X-ray source, 125 kVp and half tube current with respect to the default value provided by the manufacturer.²⁷

The CBCT scans were acquired with the acquisition settings currently in use in our department (STD) and two low dose settings (Low1 and Low2). The difference between the Low1 and STD settings is a 50% lower exposure. The Low2 protocol compared to the Low1 includes a lower frame rate, which means a 63% lower exposure with respect to the STD settings. The details of the acquisition settings are summarised in Table 1.

In this study, the STD settings were used to acquire the first CBCT scan, followed by the Low1 and the Low2 settings for the next IGRT sessions. After the acquisition of each CBCT scan, an experienced radiation therapy technologist (RTT) and a physicist examined the images to check whether the patient positioning and the evaluation of proper bladder and rectum filling could be easily performed, without any problem related to a poor image quality. A positive response meant that the next CBCT scan could be acquired with the subsequent low dose protocol. This was to reduce the risk of acquisition of inadequate images.

The CBCT image quality was graded by four radiation oncologists and two RTTs with more than 5 years of experience. The two RTTs were not involved in the preliminary check of the image quality with the physicist. The subjective evaluations were carried out for the following characteristics:

- Visibility of low contrast features;
- Visibility of high contrast features;
- Evaluation of bladder and rectum filling;
- Perceived noise level;
- Overall image quality.

The grading scale was based on four score levels:

- (1) Perfect: the CBCT image quality is comparable to the planning CT;
- (2) Good: a difference between the CBCT image quality and the planning CT can be perceived, however, it does not affect the clinical task;
- (3) Poor: the CBCT image quality is definitely worse compared to the planning CT and performing the clinical task is difficult;
- (4) Inadequate.

The raters were trained on the meaning of the image characteristics and the grading scale. A list of the images to be graded was prepared for each rater and it was regularly updated when all the images of a new patient were acquired. For each patient, the first CBCT scan and most of the CBCT scans were acquired with the STD settings. The low dose acquisitions were performed in between STD acquisitions. The Low2 acquisition settings were always used after the Low1 acquisition settings. This procedure helped to avoid an easy guess of the acquisition settings.

All the CBCT images in the list were rated by all the raters blinded to the acquisition settings. No particular indications were given on the ambient light or the grey-level mapping to perform the

Table 3. AC scores for the evaluation of the interrater agreement

Protocol	Visibility of low contrast features	Visibility of high contrast features	Evaluation of bladder and rectum filling	Perceived noise level	Overall image quality
STD	0.64	0.82	0.70	0.70	0.69
Low1	0.63	0.84	0.68	0.74	0.68
Low2	0.64	0.88	0.69	0.80	0.68

Values between 0.6 and 0.79 indicate Moderate agreement. Values between 0.8 and 0.9 indicate Strong agreement.

image evaluation. The raters were free to review the images as they normally do during the clinical practice.

Statistical analysis

To check for the reliability of the evaluations, the intrarater and the interrater agreement was evaluated by means of the Gwet AC coefficient with linear weights. The AC coefficient is an alternative measure to the κ statistic that is more robust in case of uneven distributions of the grading scores.^{28,29} As the “Poor” and “Inadequate” scores were much less frequent than the higher scores, we found the AC coefficient a more appropriate measure of the agreement. The weighted version of the coefficient takes into account the ordinal nature of the score levels, assigning a penalty term proportional to the distance between the levels. The AC coefficient ranges from -1 to $+1$ and its interpretation is the same as the κ statistic³⁰: below 0.2 indicates No agreement, $0.21 < AC < 0.39$ Minimal agreement, $0.40 < AC < 0.59$ Weak agreement, $0.6 < AC < 0.79$ Moderate agreement, $0.80 < AC < 0.90$ Strong agreement and above 0.90 Almost Perfect agreement. The AC coefficients were calculated using an R script.³¹

The effect of the low dose acquisition settings on the image quality was evaluated through VGR analysis.¹⁹ A binary mixed effect logistic regression was carried out for each image characteristic. The scores of each image characteristics were collapsed to two levels: 0 for the “Poor” and “Inadequate” score levels and 1 for the “Good” and “Perfect” score levels. The acquisition settings and the patient size were included in the regression model as fixed effects. The patient size was included in the model as a fixed effect because it affects the attenuation and the scattering of the radiation beam, thus the image quality.¹⁵

In a binary mixed effects logistic regression model, the regression coefficients of the model refer to the equation:

$$\log \frac{p}{1-p} = \beta_0 + \beta x + \gamma z \quad (1)$$

where p is the probability of outcome “1,” β is the regression coefficients vector of the fixed effects, x is the vector of the fixed effects covariates, γ is the regression coefficients vector of the random effects and z is the vector of the random effects covariates.

From equation 1, it is possible to calculate the probability p by:

$$p = \frac{1}{1 + e^{-(\beta_0 + \beta x + \gamma z)}} \quad (2)$$

In this study, p is the probability of having an adequate image quality, x refers to the acquisition setting and patient size variables and z refers to the rater and patient variables.

The statistical significance level for the regression coefficients was set to 0.05.

The “glmmTMB” R package v. 0.2.3³² was used to perform the logistic regression analysis.

Each image characteristics was analysed independently. For each image characteristics, the scores from all the raters were arranged in a single table with the following information: Patient ID, Patient size, Acquisition settings, Rater and Score. The Score values were either 0 or 1, after the binarisation process of the four score levels.

Table 4. Results of the logistic regression analysis for image quality scores of the CBCT scans of patients with size below 110 cm: full regression model including both the acquisition settings and the patient size independent variables

	Low1		Low2		Patient size	
	coefficient	p-value	coefficient	p-value	coefficient	p-value
Visibility of high contrast features	-19.8	0.99	7.09	1	-0.07	0.91
Visibility of low contrast features	-0.67	0.16	-0.76	0.11	-0.07	0.33
Evaluation of bladder and rectum filling	-30.72	0.8	-30.72	0.8	-0.09	0.52
Perceived noise level	0.07	0.89	-0.24	0.63	-0.02	0.86
Overall image quality	-0.03	0.95	-0.10	0.82	-0.03	0.74

CBCT, cone beam CT.

Table 5. Results of the logistic regression analysis for image quality scores of the CBCT scans of patients with size below 110 cm: intercept only regression model

	Constant	<i>p</i> -value	Probability of outcome “good image quality”
Visibility of high contrast features	6.4	7×10^{-11}	1
Visibility of low contrast features	5.8	0.003	1
Evaluation of bladder and rectum filling	6.7	2×10^{-16}	1
Perceived noise level	4.2	3×10^{-8}	0.98
Overall image quality	4.6	2.7×10^{-6}	0.99

CBCT, cone beam CT.

The logistic regression was performed through the following R command:

```
Fit_model<- glmmTMB(Score ~ Acquisition settings + Patient size + (1 | PatientID) + (1 | Rater), data=data table of single image characteristic, family=binomial).
```

The calculation of the probability *p* was then performed through the *predict* command.

RESULTS

Intra- and interrater agreement

The results of the intra- and interrater agreement are shown in [Tables 2 and 3](#).

The intrarater AC scores showed a level of agreement between Moderate and Almost perfect for all the characteristics and the acquisition protocols.

The interrater AC score showed a Strong agreement for the Visibility of high contrast features characteristic and a Moderate agreement for all the other characteristics.

Visual grading regression analysis

The regression coefficients of the effect of both the Low1 and Low2 acquisition settings and their *p*-values are shown in [Table 4](#). The analysis was carried out on the CBCT image quality scores of 19 patients with body profile length below 110 cm. 5 patients out of 24 were not considered suitable for the Low2 acquisition protocol. All the *p*-values are above 0.05, therefore the acquisition protocol and patient size have no significant impact on the image quality of the patients with body profile length below 110 cm. To confirm this result, an additional logistic regression was carried out by excluding both the acquisition settings and the patient size variables from the fitting model: the intercept only regression model. The likelihood ratio test between the intercept only model and the previous full model that included both the acquisition protocol and patient size variables was performed (*anova* command in R) to check whether the two variables had an influence on the image quality. The results of the intercept only regression model are shown in [Table 5](#). The results of the likelihood ratio test between the full model and the intercept only model are shown in [Table 6](#). *p*-values of the likelihood ratio test (the $\text{Pr}(>\text{Chisq})$ element of [Table 6](#)) above 0.05 mean that

the acquisition settings and the patient size variables included in the full model do not have any impact on the probability of having a good image quality. The *p*-values are above 0.05 for all the image characteristics therefore all the coefficients in [Table 4](#) can be considered as 0. From the results in [Tables 5 and 6](#), it is possible to conclude that the probability of an adequate image quality is above 0.98 for all the image characteristics, it is the same for all the acquisition settings and it does not depend on the patient size.

These results are only valid for the patients with body profile length below 110 cm and cannot be extrapolated for larger patients. Image noise increases with patient size,¹⁸ so the probability of having a good image quality could decrease. Therefore, a second logistic regression analysis was carried out on the whole data set that included the evaluation of the CBCT images of larger patients. The effect of the Low2 acquisition settings could not be assessed because the Low2 acquisition settings were not used to acquire the images of large patients.

The regression coefficients of the second logistic regression analysis and the associated *p*-values are shown in [Table 7](#). The Perceived noise level and Overall image quality characteristics show a statistically significant dependence on the patient size (*p*-value < 0.05), while the Visibility of high contrast features characteristic shows a dependence on the acquisition settings. The Visibility of low contrast features and the Evaluation of bladder and rectum filling characteristics show a statistically significant dependence on both the acquisition settings and patient size. The negative values of the coefficients indicate that, compared to the STD acquisition settings, there is a decrease of the probability of having an adequate image quality with either the Low1 acquisition setting and increasing patient size.

Besides the statistical significance, it is important to quantify how much the image quality is actually affected by the patient size and the acquisition settings. The plots of the regression models, in terms of the probability of having an adequate image quality, are shown in [Figure 2](#). For the Visibility of high contrast features, [Figure 2\(a\)](#) shows that the curves relative to the STD and Low1 acquisition settings hardly split up. Therefore, it can be concluded that the two acquisition settings are equivalent for all patient size. For the Visibility of low contrast features, the curves start to split at about 100 cm patient size. However, at 105 cm patient size the probability of having an adequate image quality

Table 6. Results of the Likelihood ratio test for the comparison of the intercept only regression model and the full model of the logistic regression analysis for image quality scores of the CBCT scans of patients with size below 110 cm.

	Output of the Log likelihood ratio test					
		Df	logLik	Chisq	Df	Pr(>Chisq)
Visibility of high contrast features	Intercept only	3	-7.5			
	Full model	6	-4.7	5.6	3	0.13
Visibility of low contrast features	Intercept only	3	-116.9			
	Full model	6	-114.9	3.9	3	0.26
Evaluation of bladder and rectum filling	Intercept only	3	-37.4			
	Full model	6	-33.6	7.6	3	0.06
Perceived Noise level	Intercept only	3	-124.2			
	Full model	6	-123.7	0.96	3	0.81
Overall image quality	Intercept only	3	-126.4			
	Full model	6	-126.2	0.51	3	0.92

Chisq, X^2 value; Df, Degrees of freedom; Pr(>Chisq), Probability of higher X^2 values; logLik, log likelihood.

drops from 0.96 to 0.93 which could not be significant in the real practice. The same holds for the Evaluation of bladder and rectum filling characteristic.

DISCUSSION

A study on the optimisation of the CBCT acquisition settings for IGRT of prostate treatments was carried out. The standard acquisition settings currently used in our department comprise a full rotation of the X-ray source, 125 kVp tube voltage and 540 mAs tube current. The full rotation of the beam allowed the large field of view of 46 cm diameter. Starting from our standard acquisition settings, two low dose protocols were defined by decreasing the exposure settings by 50% and 63%. Decreasing the tube voltage would have been an effective way to reduce the overall dose. Indeed a tube voltage of 110 kVp is suggested in the literature.¹⁸ However, 110 kVp cannot be selected on the tube voltage settings of the imaging system of the Varian Truebeam machine v. 2.7 MR3. The choice is limited to four values: 80, 100, 125 and

140 kVp. Since the manufacturer suggests 100 kVp tube voltage for the head area, using 100 kVp in the pelvis area of adult male patients would have increased the risk of acquiring inadequate images. Therefore, the low dose protocols studied in this work were defined by decreasing the exposure.

The results showed that for patients with size up to 100 cm, the use of the low dose protocols was feasible without compromising the clinical task. For larger patients, the probability of having an adequate image quality decreases with patient size and acquisition settings. This is in contrast to the conclusions of Yang et al,¹⁷ who suggested the use of low dose acquisition protocols limited to paediatric or adolescent patients with cross-sectional diameter below 25 cm, that corresponds to 78.5 cm circumference. For adult patients with cross-sectional diameter above 25 cm and below 28 cm (*i.e.* about 88 cm circumference) they suggest the use of the mid dose protocol that has twice the tube current of the STD protocol of this work. Their study was carried out on

Table 7. Results of the logistic regression analysis for image quality scores of the CBCT scans of all patients

	Low1		Patient size	
	coefficient	p-value	coefficient	p-value
Visibility of high contrast features	-2.00	0.01	-0.27	0.14
Visibility of low contrast features	-1.05	0.006	-0.25	0.0001
Evaluation of bladder and rectum filling	-2.28	0.0003	-0.44	0.007
Perceived noise level	-0.06	0.89	-0.28	0.01
Overall image quality	-0.31	0.51	-0.36	0.008

CBCT, cone beam CT.

Figure 2. Plots of the logistic regression models for each characteristic. The plots show the predicted probability of acquiring an adequate image quality for the characteristic described in each plot title. The Visibility of high contrast features is not much influenced by the patient size and the acquisition settings (a). The Visibility of low contrast features and the Evaluation of bladder and rectum filling are influenced by both the patient size and the acquisition settings (b, c, respectively). The Perceived noise level and the Overall image quality are influenced by the patient size only (d, e, respectively). The regression coefficients are reported in Table 7.

the electron density phantom (model 062, CIRS, Norfolk, VA), covered with different layers of Superflab bolus (Radiation Products Design Inc, Albertville, MN) to simulate different patient size. The image quality was quantified by the CNR. The choice of

the optimal acquisition settings was based on the CNR value of 5. This threshold was based on personal experience. The image quality metric used and its threshold value have a great influence on the optimisation of acquisition protocols based on phantoms

and it can be the reason of different conclusions. On the other hand, our findings are in agreement with the study of Wood et al.,¹⁸ where the authors showed that low dose acquisition settings can be applied to those patients classified as small or medium. Their work was based on the evaluation of the image noise calculated on the CT AEC phantom (Leeds Test Objects, Boroughbridge, UK). The CT AEC phantom is composed of elliptical polymethyl methacrylate sections with width ranging from 17.5 to 42.9 cm. The aspect ratio is 3:2. The phantom was scanned with both the Varian On-Board-Imager system and the planning CT scanner. The optimal CBCT exposure factors for different phantom width were chosen by matching the CBCT image noise with the planning CT image noise. They found that the low dose acquisition protocols are suitable for small and medium patients, that correspond to the CT AEC phantom width below 40 cm, that is with perimeter of about 100 cm.

It must be pointed out that the image evaluation carried out in this study was limited to male patients treated for prostate cancer. The use of the low dose protocols in case of other type

of treatments in the pelvis area, or female patients, has not been yet assessed.

CONCLUSIONS

In this work, we showed that a reduction of the CBCT dose in the pelvis area up to 63% is feasible without affecting the clinical imaging purpose. Patients with size below 100 cm can benefit from the Low2 acquisition settings. Patients with size above 100 cm, that can be clinically classified as obese, can still benefit from lower dose acquisition protocols but the visibility of the low contrast features could be compromised.

ACKNOWLEDGEMENT

The authors would like to thank all the staff members of the Radiation Oncology Clinic for their cooperation and support.

ETHICS APPROVAL

The Canton Ticino Ethics Committee waived the need for ethics approval and the need to obtain consent for publication of the results of this work.

REFERENCES

1. American College of Radiology. ACR–ASTRO practice parameter for image-guided radiation therapy (IGRT). 2019.
2. Franzone P, Fiorentino A, Barra S, Cante D, Masini L, Cazzulo E, et al. Image-Guided radiation therapy (IGRT): practical recommendations of Italian association of radiation oncology (AIRO). *Radiol Med* 2016; **121**: 958–65. doi: <https://doi.org/10.1007/s11547-016-0674-x>
3. National Cancer Action Team. National radiotherapy implementation group report. Image guided radiotherapy (IGRT): guidance for implementation and use. 2012.
4. Schneider U, Hälgl R, Besserer J. Concept for quantifying the dose from image guided radiotherapy. *Radiat Oncol* 2015; **10**: 188. doi: <https://doi.org/10.1186/s13014-015-0492-7>
5. Qiu Y, Moiseenko V, Aquino-Parsons C, Duzenli C. Equivalent doses for gynecological patients undergoing IMRT or RapidArc with kilovoltage cone beam CT. *Radiation Oncol* 2012; **104**: 257–62. doi: <https://doi.org/10.1016/j.radonc.2012.07.007>
6. Perks JR, Lehmann J, Chen AM, Yang CC, Stern RL, Purdy JA. Comparison of peripheral dose from image-guided radiation therapy (IGRT) using kV cone beam CT to intensity-modulated radiation therapy (IMRT). *Radiation Oncol* 2008; **89**: 304–10. doi: <https://doi.org/10.1016/j.radonc.2008.07.026>
7. Abuhaimeid A, Martin CJ, Sankaralingam M. A Monte Carlo study of organ and effective doses of cone beam computed tomography (CBCT) scans in radiotherapy. *J Radiol Prot* 2018; **38**: 61–80. doi: <https://doi.org/10.1088/1361-6498/aa8f61>
8. Marchant TE, Joshi KD. Comprehensive Monte Carlo study of patient doses from cone-beam CT imaging in radiotherapy. *J Radiol Prot* 2017; **37**: 13–30. doi: <https://doi.org/10.1088/1361-6498/37/1/13>
9. Ding GX, Munro P, Pawlowski J, Malcolm A, Coffey CW. Reducing radiation exposure to patients from kV-CBCT imaging. *Radiation Oncol* 2010; **97**: 585–92. doi: <https://doi.org/10.1016/j.radonc.2010.08.005>
10. Roxby P, Kron T, Foroudi F, Haworth A, Fox C, Mullen A, et al. Simple methods to reduce patient dose in a Varian cone beam CT system for delivery verification in pelvic radiotherapy. *Br J Radiol* 2009; **82**: 855–9. doi: <https://doi.org/10.1259/bjr/37579222>
11. Hauri P, Hälgl RA, Schneider U. No increase in effective dose from half compared to full rotation pelvis cone beam CT. *J Appl Clin Med Phys* 2017; **18**: 364–8. doi: <https://doi.org/10.1002/acm2.12150>
12. International Atomic Energy Agency (IAEA). Introduction of image guided radiotherapy into clinical practice. Report No.: 16. 2019.
13. Ding GX, Alaei P, Curran B, Flynn R, Gossman M, Mackie TR, et al. Image guidance doses delivered during radiotherapy: quantification, management, and reduction: Report of the AAPM therapy physics Committee task group 180. *Med Phys* 2018; **45**: e84–99. doi: <https://doi.org/10.1002/mp.12824>
14. Murphy MJ, Balter J, Balter S, BenComo Jr JA, Das IJ, Jiang SB, et al. The management of imaging dose during image-guided radiotherapy: report of the AAPM task group 75. *Med Phys* 2007; **34**: 4041–63. doi: <https://doi.org/10.1118/1.2775667>
15. Siewerdsen JH, Jaffray DA. Cone-Beam computed tomography with a flat-panel imager: magnitude and effects of x-ray scatter. *Med Phys.* (2001); **28**: 220–31. doi: <https://doi.org/10.1118/1.1339879>
16. Langmack KA, Newton LA, Jordan S, Smith R. Cone beam CT dose reduction in prostate radiotherapy using Likert scale methods. *Br J Radiol* 2016; **89**: 20150460. doi: <https://doi.org/10.1259/bjr.20150460>
17. Yang C-C, Yu P-C, Ruan J-M, Chen Y-C. Optimizing the target detectability of cone beam CT performed in image-guided radiation therapy for patients of different body sizes. *J Appl Clin Med Phys* 2018; **19**: 310–7. doi: <https://doi.org/10.1002/acm2.12306>
18. Wood TJ, Moore CS, Horsfield CJ, Saunderson JR, Beavis AW. Accounting for patient size in the optimization of dose and image quality of pelvis cone beam CT protocols on the Varian OBI system. *Br J Radiol* 2015; **88**: 20150364. doi: <https://doi.org/10.1259/bjr.20150364>
19. Smedby Ö, Fredrikson M. Visual grading regression: analysing data from visual grading experiments with regression models.

- Br J Radiol* 2010; **83**: 767–75. doi: <https://doi.org/10.1259/bjr/35254923>
20. Svensson E. Guidelines to statistical evaluation of data from rating scales and questionnaires. *J Rehabil Med* 2001; **33**: 47–8. doi: <https://doi.org/10.1080/165019701300006542>
 21. Båth M, Månsson LG. Visual grading characteristics (VGC) analysis: a non-parametric rank-invariant statistical method for image quality evaluation. *Br J Radiol* 2007; **80**: 169–76. doi: <https://doi.org/10.1259/bjr/35012658>
 22. Kataria B, Althén JN, Smedby Örjan, Persson A, Sandborg M, Smedby Ö, Smedby Ö, Sökjer A, H., & Sandborg, M. Assessment of image quality in abdominal CT: potential dose reduction with model-based iterative reconstruction. *Eur Radiol* 2018; **28**: 2464–73. doi: <https://doi.org/10.1007/s00330-017-5113-4>
 23. Smedby Ö, Fredrikson M, De Geer J, Borgen L, Sandborg M. Quantifying the potential for dose reduction with visual grading regression. *Br J Radiol* 2013; **86**: 31197714. doi: <https://doi.org/10.1259/bjr/31197714>
 24. Saffari SE, Löve Áskell, Fredrikson M, Smedby Örjan, Löve Á. Regression models for analyzing radiological visual grading studies-an empirical comparison. *BMC Med Imaging* 2015; **15**: 49. doi: <https://doi.org/10.1186/s12880-015-0083-y>
 25. Zhu S, Wang Z, Heshka S, Heo M, Faith MS, Heymsfield SB. Waist circumference and obesity-associated risk factors among whites in the third National health and nutrition examination survey: clinical action thresholds. *Am J Clin Nutr* 2002; **76**: 743. doi: <https://doi.org/10.1093/ajcn/76.4.743>
 26. Lean ME, Han TS, Morrison CE. Waist circumference as a measure for indicating need for weight management. *BMJ* 1995; **311**: 158–61. doi: <https://doi.org/10.1136/bmj.311.6998.158>
 27. Varian Medical systems. TrueBeam technical reference guide – volume 2: imaging. P1011696–003. 2017.
 28. Zec S, Soriani N, Comoretto R, Baldi I. High agreement and high prevalence: the paradox of Cohen's kappa. *Open Nurs J* 2017; **11**: 211–8. doi: <https://doi.org/10.2174/1874434601711010211>
 29. Quarfoot D, Levine RA. How robust are multirater interrater reliability indices to changes in frequency distribution? *Am Stat* 2016; **70**: 373–84. doi: <https://doi.org/10.1080/00031305.2016.1141708>
 30. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Med* 2012; **22**: 276–82. doi: <https://doi.org/10.11613/BM.2012.031>
 31. Gwet KL. R functions for calculating agreement coefficients.. Available from: http://www.agreestat.com/r_functions.html [2019, October 2nd].
 32. Brooks Mollie,E., Kristensen K, Benthem Koen,J.,van, Magnusson A, Berg Casper,W., Nielsen A, Brooks ME, van Benthem KJ, Berg CW, et al. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *R J* 2017; **9**: 378–400. doi: <https://doi.org/10.32614/RJ-2017-066>