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ORIGINAL ARTICLE

Dose calculation and treatment plan optimization including imaging dose from kilovoltage cone beam computed tomography

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ABSTRACT

Background. With the increasing use of cone beam computed tomography (CBCT) for patient position verification and radiotherapy treatment adaptation, there is an increasing need to develop techniques that can take into account concomitant dose using a personalized approach.

Material and methods. A total of 20 patients (10 pelvis and 10 head and neck) who had undergone radiation therapy using intensity modulated radiation therapy (IMRT) were selected and the dose from kV CBCT was retrospectively calculated using a treatment planning system previously commissioned for this purpose. The imaging dose was added to the CT images used for treatment planning and the difference in its addition prior to and after the planning was assessed.

Results. The additional isocenter dose as a result of daily CBCT is in the order of 3–4 cGy for 35-fraction head and neck and 23–47 cGy for 25-fraction pelvis cases using the standard head and neck and pelvis image acquisition protocols. The pelvic dose is especially dependent on patient size and body mass index (BMI), being higher for patients with lower BMI. Due to the low energy of the kV CBCT beam, the maximum energy deposition is at or near the surface with the highest dose being on the patient's left side for the head and neck (~7 cGy) and on the posterior for the pelvic cases (~80 cGy). Addition of imaging dose prior to plan optimization resulted in an average reduction of 4% in the plan monitor units and 5% in the number of control points.

Conclusion. Dose from daily kV CBCT has been added to patient treatment plans using previously commissioned kV CBCT beams in a treatment planning system. Addition of imaging dose can be included in IMRT treatment plan optimization and would facilitate customization of imaging protocol based on patient anatomy and location of isocenter.

The dose as a result of imaging performed for patient position verification has traditionally been ignored in radiation therapy. Prior to advent of cone beam computed tomography (CBCT) systems, this dose was generally in the order of 2–4 cGy per weekly portal imaging. The increased use of image-guided radiation therapy (IGRT), often accomplished using CBCT systems, lead to more frequent imaging of the patients. It is common practice to image patients; especially those treated using intensity-modulated radiation therapy (IMRT) techniques, on a daily basis. In addition, use of CBCT instead of portal imaging generally exposes a larger volume of normal tissues to imaging dose.

There have been many investigations to quantify the dose from CBCT imaging. The majority of work done in this area has been performed by making measurements in phantom or using Monte Carlo methods to calculate imaging dose [1–17]. Also, because of the ever-evolving nature of this relatively new imaging modality, differences in design between different manufacturers, variation in imaging techniques used to image different anatomical sites, and the efforts made to reduce the dose by the users and manufacturers, there is a wide variation in the dose encountered from CBCT imaging, as reflected in the literature.

There is therefore the need to increase and consolidate the amount of data on imaging dose to actual

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patients, especially for kilovoltage (kV) CBCT systems. Furthermore, commercial treatment planning systems capable of calculating concomitant kV CBCT imaging dose are not yet available and the feasibility of including CBCT dose in an advanced treatment plan optimization process has yet to be reported.

The present work uses the imaging beams previously commissioned in a commercial treatment planning system to compute the imaging dose, and adds it to the therapeutic dose, for a total of 20 patients treated to head and neck and pelvic regions. The dose magnitude within the patient and sensitive organs, its effect on dose distribution within and outside the treatment volume, and its variation with the location of isocenter, patient size and body mass index (BMI), have been studied. The imaging dose has also been calculated prior to treatment planning to investigate the feasibility of including it in the treatment plan optimization process, and the impact of the addition of this concomitant dose on the delivery parameters of the optimized treatment plans has been assessed. Similar work has previously been performed for Megavoltage CBCT [5,6] but this is first of such investigations involving kV CBCT.

Material and methods

The dose from kV CBCT has been retrospectively added to 20 patient treatment plans, 10 head and neck and 10 pelvis cases, under an Institutional Review Board (IRB)-approved study. Overall additional dose to the patient, location of maximum dose (hot spot), and effect of the kV CBCT dose on organs within and outside the treatment volume have been evaluated. The kV CBCT dose is the result of daily imaging using an Elekta X Ray Volume Imaging (XVI) system (Elekta, Atlanta, GA, USA). Beam data collection, modeling, and evaluation of calculation accuracy for beams generated by the XVI system in the Pinnacle treatment planning system (Philips, Milpitas, CA, USA) has been previously described and evaluated [18]. This system had previously been modified to accommodate dose calculations in the kilovoltage energy range [19–22].

The selected patients have all been treated using IMRT on an Elekta Synergy linear accelerator and subject to daily CBCT imaging using the XVI system employing the default imaging protocol for the respective anatomical site. The 10 primary head and neck cases were each treated definitively to a total dose of 70 Gy in 35 fractions using IMRT plans with 6 MV photons. Treatment included an initial dose of 50 Gy using a nine-field plan and one or two additional seven- or nine-field boost plans to 70 Gy. The pelvic cases were either endometrial or cervix carcinomas treated using seven- or nine-field plans of 10 MV photons to a total dose of 45 Gy in 25 fractions. The protocol used to image head and neck cases utilizes a 100 kVp, 0.1 mAs beam (10 mA, 10 ms) collimated with the S20 cassette with the x-ray tube rotating from 345 to 190 degrees (IEC scale) acquiring approximately 360 frames. The pelvis protocol utilizes a 120 kVp, 1 mAs beam (25 mA, 40 ms) collimated with the M20 cassette with the x-ray tube rotating from 270 to 270 degrees (a full 360° rotation) acquiring approximately 650 frames. No additional filtration was used in these acquisitions, i.e. F0 filter was used.

At the conclusion of treatment, imaging beams were added to each patient's treatment plan and computed. The beams were added as arcs but computed discretely at 5° intervals as explained previously [18,22]. The regions of interest used for dose evaluation were all drawn by the same person on all the images. These included bladder, rectum, kidneys, femurs, pelvic bones and small bowel for pelvis and spinal cord, parotids, brainstem, cochleae, eyes, optic nerves and chiasm, larynx and esophagus for head and neck ones. The treatment couch was removed prior to planning for all cases as is routine for treatment planning. Accounting for the couch would impact dose distribution primarily in the regions close to the couch and is couch-dependent. This is estimated to reduce the dose by up to 10% for patients studied here, and using the iBEAM evo couchtop (Elekta), in the patient volume near the couch, but has little effect elsewhere. The daily shifts of the patients were also extracted from Mosaiq record and verify system (Elekta) and saved for further analysis.

Furthermore, all treatment plans were copied, the beams were reset, and the plans re-optimized with the same optimization parameters as the initial plan but with the computation of CBCT beams in the beginning. This, in effect, accounted for imaging dose prior to optimization in the treatment plans.

Results

Figures 1 and 2 demonstrate isodose distributions and dose-volume histograms (DVH) resulting from daily CBCT imaging. The imaging dose calculated here is simply the absorbed dose, and not the effective one. Examining the imaging dose on a per-treatment basis, head and neck imaging using the above protocol delivers a daily dose which amounts to less than 0.1% of the daily treatment dose whereas pelvic imaging delivers a dose equivalent to approximately 1.7% of the daily treatment dose to the patient.

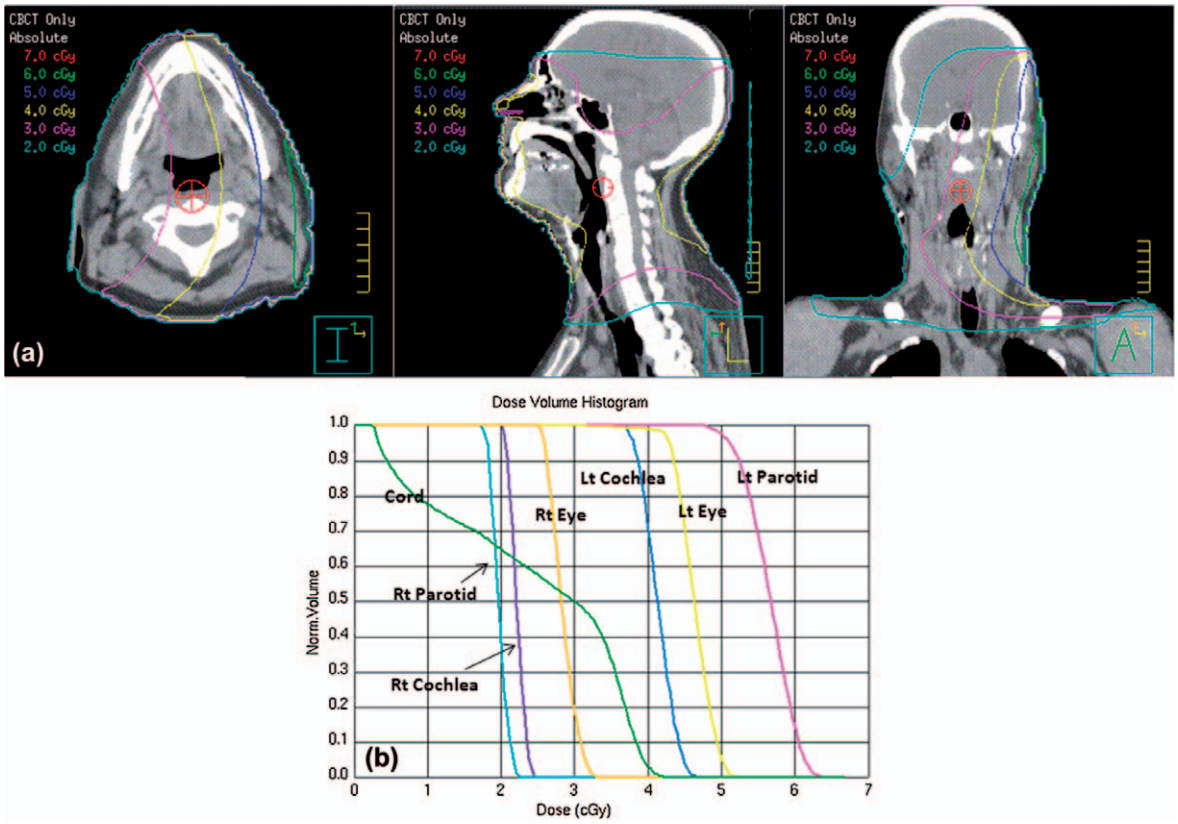

Figure 1. Isodose distribution (a) and dose volume histogram (b) demonstrating imaging dose from 35 fractions of head and neck imaging for one patient.

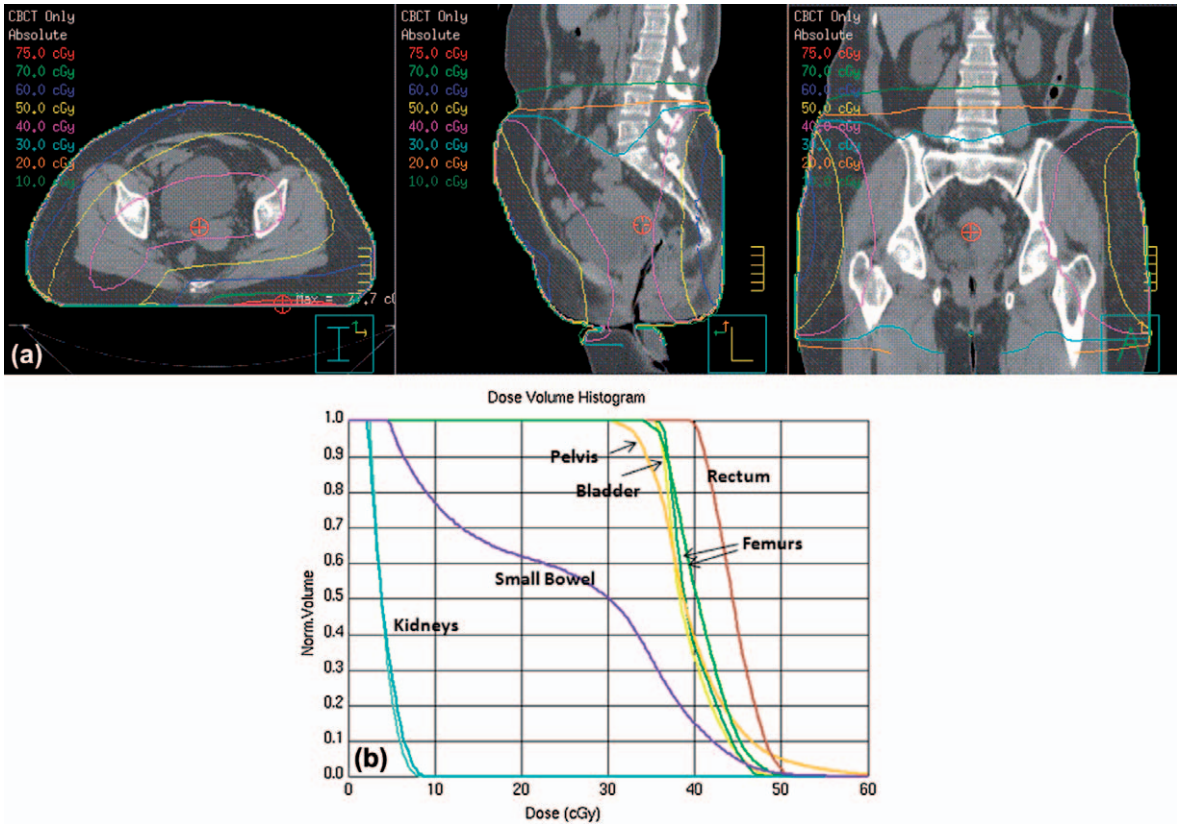

Figure 2. Isodose distribution (a) and dose volume histogram (b) demonstrating imaging dose from 25 fractions of pelvis imaging for one patient.

Table I. A summary of doses delivered as a result of daily CBCT imaging to certain critical organs for head and neck cases (35 fractions) and pelvis cases (25 fractions).

Head and neck cases			Pelvis cases		
	Dose (cGy)			Dose (cGy)	
Organ	Median	Range	Organ	Median	Range
Rt Eye	2.9	0.8–3.0	Rt Kidney	4.8	2.7–26.2
Lt Eye	4.7	1.2–4.8	Lt Kidney	5.3	3.3–31.1
Rt Parotid	1.9	1.7–2.2	Bladder	40.0	23.4–52.4
Lt Parotid	5.7	5.5–5.8	Rectum	39.9	27.2–48.6
Cord	2.6	1.8–3.1	Small Bowel	38.0	25.6–46.3
Rt Cochlea	1.9	1.7–2.2			
Lt Cochlea	3.8	3.4–4.1			

Table I summarizes the doses delivered to certain critical organs from daily imaging. A detailed compilation of patient-specific data and doses delivered to patients and various organs can be found in Supplementary Table I, available online at http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.875626. The dose to bony structures (femurs and pelvis) is under-estimated by a factor of 2–3 due to inability of the planning system to accurately compute dose to bone.

Head and neck imaging results in a much lower dose than pelvic one due to its utilization of lower kVp and mAs and fewer frames. However, because of the 345–195° rotation range, the dose to the patient's left side is higher than right and the maximum dose is always on the left side of the patient. The isocenter dose is 3–4 cGy and the maximum dose is approximately 7 cGy, as seen in the Supplementary Table I available online at (http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.875626). Due to the lack of large variation in patients' head and neck sizes, there is not a noticeable variation of dose among patients. For the same reason, there is little variation in organ doses between patients and no correlation between BMI and isocenter dose; Supplementary Figure 1 available online at (http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.875626) demonstrates this.

Pelvic imaging results in higher doses with a magnitude between 70 and 80 cGy at the maxima (close to skin) and 30–40 cGy at the isocenter. The maximum dose is always on the posterior of the patient in the cases studied because the isocenter is closer to the posterior of the patient than anterior in all cases. Due to the variation of patients' sizes in the pelvic region, there is an appreciable difference in the dose given to different patients and their organs. For example, isocenter dose ranges from 22.7 to 46.7 cGy. There is also an inverse relationship between BMI and isocenter dose for the pelvic cases (Figure 3).

Re-optimization of the plans after the computation of imaging beams produced identical dose distributions but with fewer monitor units and, for the most part, fewer control points (segments). The monitor units of these plans were on average 4% lower than the original plans, with a maximum value of 7%, and the number of segments was

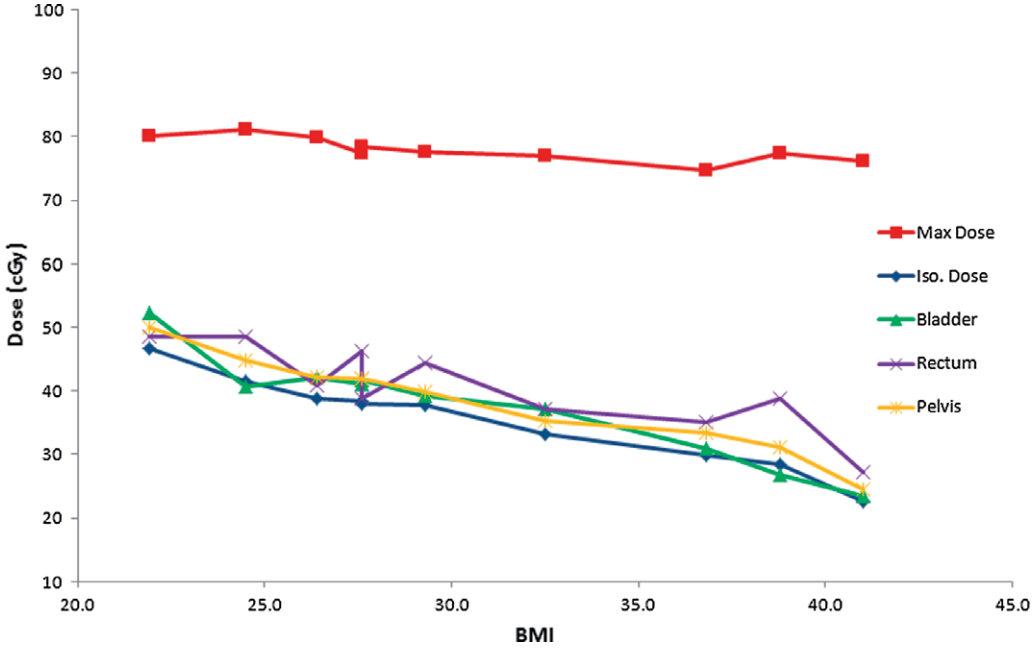

Figure 3. Correlation of isocenter, maximum, and several organ doses with body mass index for 25 fractions of pelvis imaging for 10 patients. Organ doses are mean dose values. The dose to pelvic bones is likely to be underestimated by a factor of 2–3 due to the inability of planning system to compute the dose accurately in bone. The BMI was calculated on the day of simulation.

lowered by an average of 5% with a maximum value of 10%. The reduced number of segments decreases the treatment delivery time slightly. Supplementary Table II (available online at http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.875626) lists the results of this re-optimization.

Discussion

This study retrospectively calculated kV CBCT doses to 20 patients who had undergone radiation therapy to the head and neck and pelvic regions using a treatment planning system. The planning system had previously been commissioned for this purpose and shown to compute the dose to a good degree of accuracy except in bony structures [22]. Comparison of the data in Supplementary Tables I and II, available online at (http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.875626) with data presented by Spezi [14] indicates comparable results for the pelvic organs but lower dose for the head and neck ones.

Besides the utility of the system to compute imaging dose retrospectively, it can also be used to compute imaging dose prospectively in order to use it for IMRT optimization, hence accounting for the imaging dose at the time of treatment planning. Calculating the imaging dose and optimizing the plan based on that not only takes into account the imaging dose and its distribution but also results in plans with fewer monitor units and control points. This is more relevant for pelvis plans (in this study) as the dose from head and neck imaging is much less than the treatment dose. To the best of our knowledge, this is the first time that concomitant dose from kV CBCT devices is included in the treatment plan optimization process. It should be noted here that this reduction of monitor units and control points is directly related to the dose delivered from imaging, which is in turn dependent on the technique used. So if an imaging protocol utilizing higher energy and tube current/time is used, this reduction is more appreciable. However, if a low dose protocol, similar to the ones described by Yan et al. [23,24] is employed, this reduction is less appreciable or non-existent.

The correlation between BMI and isocenter dose observed here is more appreciable than the weak correlation observed between BMI and dose by VanAntwerp et al. [25], who studied this for Megavoltage CBCT imaging. There is also an inverse correlation between BMI and organ doses as observed in Figure 3. The strong dependence of imaging dose on BMI observed here, as opposed to the weak one observed for Megavoltage imaging, can be explained in terms of differences in imaging beam qualities. A 6 MV imaging beam has a slow drop-off in dose with depth whereas a 120 kVp one has a much sharper one, hence the larger the patient, the less of kV imaging dose reaches the isocenter and internal organs, relative to MV beam.

Besides the patient size and BMI, another factor which affects the critical organ doses from imaging is the location of isocenter. This could be a factor in whether or not a critical organ may be inside the imaged volume. For example, in the case of pelvis patient 2 in Supplementary Table I, available online at http://informahealthcare.com/doi/abs/10.3109/0284186X.2013.875626, the isocenter was more superior than other cases hence the kidneys received significantly higher doses compared to other patients. The location of isocenter, therefore, could be used to decide what cassette or field size is appropriate for imaging any particular patient, hence customizing the imaging protocol used.

As for the imaging protocols used in this study, there are variations of these with new installations and software releases. The protocols can also be altered by the users. So, care must be exercised when using this data to estimate patient doses obtained with different imaging protocols. For example, the pelvis protocol used in this study (120 kVp, 25 mA, 40 ms, M20 cassette, F0 filter) is different than one utilized on newer Elekta XVI installations [120 kVp, 40 mA, 40 ms, M20 cassette, F1 (Bowtie) filter]. For comparison purposes, imaging dose to pelvic cases were also computed using this newer protocol. These calculations show an increase to isocenter and mean organ doses by 20–30%, which is due to a combination of higher mAs used in this protocol (resulting in a 60% increase in dose), and decrease in dose due to the use of bowtie filter. Dose reduction as a result of introduction of bowtie filter (keeping mAs constant) is estimated to be 30% by the planning system which matches that observed by Downes et al. [12]. It is also worth noting that the imaging doses reported here are calculated under the assumption that only one daily CBCT of the patient is taken. In the event that patient imaging is repeated after the shifts and/or at the end of the each treatment, there is an obvious increase in the magnitude of the dose.

Finally, an evaluation of daily shifts showed that there were only 13 instances where the total root mean square shift was more than 1 cm (with a 1.3 cm maximum) for the head and neck, and 14 instances where the total shift was more than 1.5 cm (with 2.1 cm maximum) for the pelvic cases. Even though the patients were shifted accordingly on a daily basis, the CT isocenter was used as the basis of daily imaging and there were no repeat imaging or adaptive planning performed.

Information presented here can be used to optimize imaging protocols to minimize the dose to sensitive organs, i.e. customizing imaging for each patient by computing the imaging dose prior to start of treatment, choosing appropriate imaging protocol and field size, and optimizing the plan (in case of IMRT treatments) while accounting for the imaging dose. This would in effect result in a personalization of dose optimization, and accounting for imaging dose in addition to therapeutic dose, in image-guided radiation therapy.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Supplementary material available online

Supplementary Figure 1.
Supplementary Table I.
Supplementary Table II.