



Review Article

Cone beam CT dose optimisation: A review and expert consensus by the 2022 ESTRO Physics Workshop IGRT working group



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ABSTRACT

Image guided radiotherapy (IGRT) using kilovoltage cone-beam CT (CBCT) has become an indispensable tool to ensure the geometric accuracy of radiotherapy treatment delivery. Although significant technical advances have been made in reducing imaging dose, the repeated imaging procedures can still accumulate significant dose to healthy tissues. Despite the widespread use, we still lack clear guidance for optimisation and widely accepted frameworks for evaluating the quality and suitability of CBCT imaging protocols. To address this gap, the 2022 European Society for Radiotherapy and Oncology (ESTRO) Physics Workshop focused on image-quality and imaging-dose optimisation for IGRT using CBCT. This publication represents a review and an expert consensus of the 2022 ESTRO Physics Workshop IGRT working group. Here we aim to provide practical advice for optimising and maintaining CBCT imaging protocols to meet the needs of local procedures and patient populations. The review includes summaries of the current status of CBCT use and optimisation for IGRT in adults and paediatrics, an overview of currently available guidelines, and finally practical guidance on optimising and implementing CBCT imaging protocols for local IGRT treatments and patient populations.

Introduction/Overview

Image-guided radiotherapy (IGRT) uses imaging technologies based on x-rays, magnetic resonance imaging (MRI), positron emission

tomography, ultrasound, or surface optical scanning to facilitate accurate planning and delivery of radiotherapy [1,2]. The inclusion of imaging technologies during radiotherapy planning allows treatments to be personalised to the geometry of each patient's tumour and healthy

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tissues. Currently, computed tomography (CT) is the gold standard for treatment planning imaging as it provides tissue information needed for the associated absorbed radiation dose calculations [3]. The subsequent use of frequent imaging throughout treatment delivery improves the geometric accuracy of the administered treatment. By increasing geometric accuracy, IGRT has enabled modern treatments to achieve enhanced target conformity and reduced target margins [4,5]. Smaller treated volumes allow modern radiotherapy treatments to escalate doses to tumours, thereby improving rates of tumour cure, while simultaneously sparing doses to healthy tissues, thereby minimising rates of side effects [1].

Today, the most common IGRT modalities use ionising radiation and include megavoltage (MV) portal imaging, fluoroscopy, CT, and MV or kilovoltage (kV) cone-beam CT (CBCT) [6]. From a technical point of view, these modalities differ in dimensionality (i.e., planar or three-dimensional), temporality (i.e. static or captures tissue motion), imaging beam energy (kV or MV) and associated dose. The radiation dose associated with IGRT modalities introduces a potential detriment as the excess imaging dose delivered to healthy tissues increases the risk of radiation-related side effects, such as second primary cancers [7], fertility complications [8,9], endocrine insufficiency [10], and cataract formation [11]. For example, a 5 % discrepancy in the treatment dose can result in actual variations in tumour response and impact organs at risk [12–14]. Therefore, AAPM TG-180 recommends considering the imaging dose as part of the total treatment dose if the imaging dose is approximately 5 % of the therapeutic target dose or more [15]. However, knowing when to consider imaging dose as part of the total treatment dose requires a more general understanding of imaging dose levels in all cases.

Importantly, the principles of radiation protection provide a framework for medical applications of ionising radiation rooted in two pillars: justification and optimisation [16,17]. The pillar of justification requires that the benefit of a radiation exposure be sufficiently large to offset/outweigh the associated radiation detriment. IGRT use and its modalities can be justified by its ability to realise benefits to the treatment, such as detecting potential set up errors, achieving the required geometric accuracy for the treatment margins or steepness of dose gradients, or clearly visualising the anatomic region aimed for matching, among other factors. The principle of optimisation stipulates that radiation doses should be kept as low as reasonably achievable (ALARA). Therefore, it is necessary for medical physicists to optimise IGRT imaging procedures to ensure the lowest-possible radiation doses for a specific task, without compromising the added value for the patient. IGRT imaging protocol optimisation involves many, often conflicting goals, such as providing sufficient image quality for the task of accurate

localisation, lowering imaging-associated dose, ensuring patient tolerability, providing comprehensive field of view, and shortening acquisition time. Consequently, finding the right balance can be challenging (Fig. 1).

In addition to the multiple goals involved in IGRT imaging optimisation, the optimisation problem is further complicated by the many parameters that may be modified in pursuit of the optimisation goals. Although the main principles of radiation-based imaging optimisation are well-known (e.g., promoting kV energies over MV, optimising image dimensions, preferring 2D orthogonal images over 3D imaging, for example, when appropriate) specific parameters such as peak kilovoltage (kVp), tube current–time product (mAs), and imaging frequency have less obvious solutions. Critically, the currently available guidelines stop short of providing practical advice to support end users (i.e., physicists and radiation therapists (RTTs)) to manage all competing objectives while optimising imaging systems for IGRT.

To address this gap, the 2022 European Society for Radiotherapy and Oncology (ESTRO) Physics Workshop focused on image-quality and imaging-dose optimisation for IGRT. To keep the scope of our task manageable, we limit our focus to the most common ionising-radiation imaging modality used in IGRT: kV-CBCT (hereafter referred to here as “CBCT”). We present a review and an expert consensus of the ESTRO IGRT imaging optimisation working group and provide practical advice for optimising and maintaining CBCT imaging protocols to meet the needs of local procedures and patient populations. Providing quantitative benchmarks for imaging protocols or reference doses, which can be found published elsewhere [15,18], was outside the scope of this manuscript. The sections that follow include summaries of the current status of CBCT use and optimisation in adults and paediatrics, an overview of currently available guidelines, and finally practical guidance on optimising CBCT imaging protocols and their clinical implementation to local treatments and patient populations.

CBCT Use and Optimisation in IGRT

An international survey of imaging practices, from 97 radiotherapy centres in nine countries found that most centres have CBCT attached to at least some of their linear accelerators (linacs) and use CBCT imaging for most treatment fractions delivered on those linacs [19]. However, the vast majority of CBCT systems attached to linacs lack the ability to automatically optimise imaging conditions as some diagnostic CT scanners do via automatic exposure control systems, and therefore require manual optimisation by end users. Furthermore, reports from several centres suggest there is much to be gained from optimising the standard ‘one size fits all’ manufacturer CBCT settings to minimise

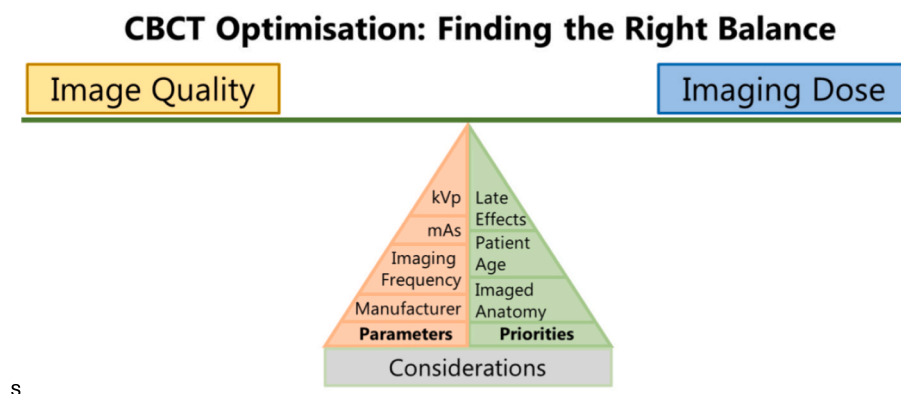


Fig. 1. Diagram demonstrating the competing objectives (blue and yellow) involved in optimising imaging protocols for image-guided radiation therapy (IGRT) and important considerations (red and green triangles) in the optimisation. Items in the red triangle represent parameters one may be able to manipulate that will impact imaging dose and/or image quality. Items in the green triangle represent considerations that inform why one might prioritize imaging dose or image quality over the other for a particular patient. Abbreviations: mAs = tube current and exposure time product; kVp = kilovoltage peak. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

patient dose while maintaining clinically acceptable images [20–23].

CBCT protocols are typically optimised to achieve the objective of either improved image quality (which may require an increase in dose) or reduced dose. The optimisation objective can be pursued by adjusting scanning parameters such as mAs, number of projections, angular span of the scan (e.g. 200° vs 360°), superior-inferior scan length (i.e., the longitudinal field of view), and time of acquisition (time needed to complete a full gantry rotation). Energy (kVp) adjustment is possible but requires additional calibrations if the desired energy is not already in use. Hence, previous studies have shown that low-dose protocols should aim to reduce mAs instead of kVp to better preserve image quality [24]. Acquisition parameters directly affect the image noise level, low-contrast detection, and contrast-to-noise ratio (CNR), but have minimal impact on uniformity, Hounsfield Unit (HU) accuracy and linearity, and spatial resolution [25]. Other straightforward changes include modifying the frequency of imaging (e.g., daily versus weekly) [26], reducing scan length or field of view (FOV), and limiting the number of projections and/or angular range acquired, all of which affect the dose to the patient. For example, reducing the projection arc can significantly reduce dose to the lens of the eyes or to contralateral organs such as the lung, if set up correctly [27]. Organ doses can be significantly reduced by reducing the FOV, employing a bow-tie filter [28], or introducing a low-energy kV filter similar to the titanium filter available for the Varian TrueBeam [29]. For 4D-CBCT imaging procedures, intrafraction presets (nominal acquisition interval) [30] and gantry speed [31] have been investigated as optimisation parameters. Likewise, employing kV planar imaging [32] can reduce dose burden where suitable.

However, maintaining sufficient image quality for the ultimate purpose of IGRT should remain the first priority as the potential errors of displacement of the therapeutic dose due to insufficient image quality can outweigh small reductions in imaging dose (Fig. 1).

Imaging optimisation for adult patients

This section summarises published work on optimising adult IGRT imaging procedures and the parameters modified to achieve optimal image quality and/or dose in adult patients based on a broad search of published research studies. Our search aimed to identify studies optimising CBCT to improve image quality and/or reduce patient dose in adult IGRT. Search engines used were ‘Google Scholar’ and ‘PubMed’ and search terms in both engines were ‘Image guided radiotherapy optimisation’ and ‘CBCT optimisation’. Sixteen relevant studies were selected for the purposes of this overview. Table 1 provides a summary

of the literature considered.

Protocol optimisation in literature.

The 16 studies emphasised that separate protocols may be needed for different patient sizes, body sites, and applications. One study reported reducing CBCT dose for 92 % of patients imaged with abdominal modes by setting up 100, 110 and 125 kVp beam energies with reduced mAs compared to default protocols [23]. However, other studies have shown that some imaging protocols might require optimisation to improve the detectability of small-size or low-contrast regions, which would result in an increase of dose. Mao et al. [25] tested 26 protocols for intracranial stereotactic radiosurgery (SRS) localization. They concluded that although default manufacturer CBCT acquisition protocols were designed with limited dose to the patient, SRS patients would benefit from better visual detection of soft tissue, achieved by increasing mAs with a proportional increase in the imaging dose. Furthermore, SRS treatments are typically characterised by fewer total fractions, so a higher imaging dose per fraction may still result in an equivalent, or even lower total cumulative imaging dose than conventional treatments using lower-dose IGRT protocols. To achieve the flexibility to reduce dose when possible and improve image quality (by increasing dose) when needed, Wood et al. suggested creating size-based protocols with accompanying clear criteria for selecting the appropriate protocol for each patient [21]. Their implementation resulted in reduced dose compared to standard protocols for 57 % of patients and higher-than-standard dose for 13 % of patients who required superior image quality. Similarly, a study by Khan et al. reported optimising protocols for patient size and treatment-specific sites and modalities [22]. They optimised some protocols to reduce patient dose by lowering the mAs of default manufacturer CBCT protocols for the thorax and abdomen and increased the imaging dose in other protocols to improve image quality for applications in SRS by varying the mAs. Finally, they optimised a pelvis protocol to reduce imaging artefacts from bowel gas and metal implants by reducing the speed of acquisition and increasing the number of projections. Altogether, Khan et al. reported 52 % of patients (in a cohort of 1185 patients) received a reduced dose compared to default protocols and 12 % received a higher dose than the default protocols for the purpose of improved image quality [22].

Importantly, the studies considered here revealed heterogeneous procedures for evaluating image quality of optimised IGRT protocols. Evaluations involved either quantitative (by assessing image quality factors such as CNR, noise, contrast, resolution) or qualitative measures (by evaluating image quality on a rating scale) using phantoms and patient images. Most studies evaluated image quality using phantoms,

Table 1

Summary of literature focusing on cone-beam computed tomography optimisation in adult tumour sites, including the main aim of the publication, methods used, dose assessment performed and image-guided radiation therapy system used.

Author / Year	Body Region	Image Quality	Dose Assessment	Dosimeter	Vendor
Roxby et al. 2008 [29]	Pelvis	Phantom ^a , Patients	CTDI _w	Ion Chamber ^c	Varian ^f
Ding et al. 2013 [28]	Head, Thorax, Pelvis	—	Dose-Volume	Treatment Planning System, Monte Carlo	Varian ^{g,h}
Liao et al. 2015 [37]	Head, Thorax, Pelvis	—	CTDI _w , CTDI _{air}	Ion Chamber ^d	Elekta ⁱ
Wood et al. 2015 [21]	Pelvis	Phantom	Dose-Volume	Monte Carlo	Varian
Elstrom et al. 2016 [34]	Head	Phantom ^a	—	—	Varian
Santoso et al. 2016 [31]	Thorax	Phantom ^a	Dose-Volume	Ion Chamber ^c	Varian
Mao et al. 2018 [25]	Head	Phantom ^{a,b} , Patients	Cone-Beam Dose Index	Ion Chamber ^d	Varian ^j
Yang et al. 2018 [40]	Thorax, Pelvis	Phantom	CTDI _w	Scanner Console	Varian ^h
Liang et al. 2019 [30]	Thorax	Phantom ^b	—	—	Elekta
Xu et al. 2019 [26]	Thorax	—	Dose-Volume	Ion Chamber	Varian
Agnew et al. 2020 [33]	Head, Thorax, Pelvis	Phantom ^a , Patients	—	—	Varian ^h
Chan et al. 2020 [32]	Pelvis	Phantom ^b	—	—	Varian ^f
Ordóñez-Sanz et al. 2021 [23]	Pelvis	Phantom ^a , Patients	CTDI _w	Ion Chamber ^d	Varian
Khan et al. 2022 [22]	Head, Thorax, Pelvis	Patients	CTDI _w , CTDI _{air}	Ion Chamber ^d	Varian ^h
Martin and Abuhaimeed 2022 [77]	Thorax, Pelvis	—	Dose-Volume	Monte Carlo	Varian

Abbreviations: CTDI: computed tomography dose index; CTDI_w: weighted CTDI; CTDI_{air}: in-air CTDI; CTDI_{vol}: volume CTDI; kV: kilovoltage; MV: megavoltage; MDCT: multi-detector computed tomography; PMMA: polymethyl methacrylate; RO: radiation oncologist; CNR: contrast-to-noise ratio; ROI: region of interest; RTT: radiation therapist; QA: quality assurance; mAs: milliampere-seconds.

CATPHAN, ^bAnthropomorphic, ^cFarmer Chamber, ^dPencil Chamber, ^eIBA CC13, ^fTrilogy, ^gOBI, ^hTrueBeam, ⁱSynergy, ^jEdge.

such as CIRS (ATOM® anthropomorphic and M62) or CATPHAN (504 and 600) [21,23,25,29–31,33,34]. Some studies acquired patient images alone [22,32] or in addition to phantom studies [23,33], and assessed the extent to which image quality improved. Other studies avoided physical experiments altogether via computational simulated experiments such as simulating the imaging technique and the resulting images of simulated phantoms or simulation-produced patient images [15,19,28].

Image quality and dose measurement methods.

There was considerably more consistency among dose-evaluation methods than was seen among image quality assessments (Table 1). Most studies evaluated dose using the standard PMMA phantom and a pencil-type ionisation chamber [23], from which the standard weighted computed tomography dose index (CTDI_w) and dose-length product (DLP), developed for diagnostic CT scanners, were calculated for CBCT equipment (Table 1). Other studies provided dose estimates for computational experiments most often involved Monte Carlo simulations, although others have proposed more pragmatic, accessible methods to estimate the dosimetric effects on patients using existing third-party dose-calculation software [35]. Lastly, a recent study by Djukelic et al. [36] proposes a pragmatic approach using commonly available equipment such as a standard 0.6 cc Farmer chamber with water-equivalent slab phantoms when CTDI phantoms and pencil chambers are not available.

Considerations for choosing the appropriate imaging protocol.

Importantly, after optimised IGRT protocols are developed, it is essential to establish a robust technique for choosing the correct protocol for each individual patient [21]. Ordonez-Sanz et al. [23] selected the appropriate protocol among those that were optimised for patient size based on the CTDI_{vol} dose indicator from the patient planning CT scan. Other centres based the choice on the patient diameter defined by maximum lateral and anterior-posterior planning CT separation [22,33]. Additional criteria for selection have included patient weight or BMI, although weight-based measures can be misleading with regard to radiation attenuation properties in the area of concern [21].

Vendor representation in literature.

It is worth noting that most of the identified studies were carried out for Varian CBCT systems (i.e., TrueBeam or Clinac iX) [21–23,33], while studies of onboard imaging systems provided by other manufacturers were limited [37]. This leaves a critical gap in knowledge for many departments for whom manufacturer-specific optimisation recommendations are unavailable. The limited generalizability of published results further increases the demand for a standardised procedure to be followed for IGRT imaging optimisation.

Based on our summary, we conclude that, despite the wealth of literature related to image-parameter optimisation for applications in IGRT, we still lack clear guidance for optimising IGRT imaging protocols, recommendations for optimal IGRT imaging parameters, and widely accepted frameworks for evaluating the quality and suitability of IGRT imaging protocols. With imaging in radiotherapy being well established and increasingly relied upon to safely and accurately treat smaller planning target volumes, the focus is now turned to local optimisation of IGRT by physicists and RTTs. Under United Kingdom [38] and European Union [39] regulations, dose must be kept ALARA and image quality must be sufficient for purpose. There is much scope for optimising the standard ‘one size fits all’ manufacturer settings, in terms of minimising patient dose whilst maintaining clinically acceptable images [40]. Most studies concluded that default protocols by manufacturers can be adapted, based on patient size and site, so that patients receive less dose for the same image quality. In most instances, the images from optimised protocols are of sufficient quality for clinical use. However, situations exist (e.g., larger patients, SRS applications) for which higher-dose settings may be appropriate and warranted.

Imaging optimisation for paediatric patients

This section provides an overview of aspects of IGRT imaging optimisation specific to paediatric treatments. Our review considered international surveys of clinical practices and studies of dose distributions and low-dose protocols for paediatric patients. A complementary table to Table 1 for paediatrics is published elsewhere [41].

Clinical practice patterns in the literature.

Four surveys investigated IGRT practice patterns for children [41–44], although minimal emphasis was placed on optimisation. Alcorn et al. reported that paediatric IGRT use varied with tumour location (i.e., 98 %–100 % of patients with brain/head and neck tumours [44] and 20 %–100 % of patients with abdominal/pelvic tumours received IGRT [42]). A large North American survey reported that 3D and daily imaging were the preferred modality and frequency, respectively, for almost all paediatric diagnoses [44]. However, another survey revealed that application of adult IGRT protocols (35 %) and imaging frequencies (74 %) to paediatric patients was common [43]. Lastly, a European survey [41] revealed consensus for technical CBCT acquisition settings for brain/head targets but large variation in settings for abdominal targets. Importantly, the North-American survey [44] provided a detailed decision tree to guide the physician and physicist toward selecting the most appropriate imaging modality (3D versus 2D) and frequency (daily or less) for paediatric IGRT.

Considerations for paediatric IGRT protocol optimisation

Large, age-related anatomic variability among paediatric patients and heterogeneous paediatric diagnoses necessitate specific optimisation of body-site- and size-specific IGRT protocols relevant to paediatric populations. Additionally, the UNSCEAR Committee found that children are more radiosensitive than adults for about 25 % of the considered cancer types, including leukaemia, skin cancer and thyroid, breast and brain tumours [45]. Imaging using kV energies can deliver considerable doses to bony structures (i.e., 2 to 3 times higher than the dose in soft tissues and 9 to 29 cGy per abdominal CBCT [46]), necessitating particular attention to the potential increase in risk of leukaemia due to irradiation of the bone marrow. However, evaluating dose deposition from optimised imaging protocols in children is non-trivial. Dose-distribution studies have shown that dose from CBCT imaging systems deposit larger doses in paediatric phantoms and critical organs [45,47] compared to adult phantoms. Notably, paediatric dose-distribution studies have often applied standard protocols developed for adult patients to paediatric phantoms. Hence, the larger dose magnitudes seen in child-sized phantoms can be partly explained by adult-designed protocols being applied in a paediatric setting. The Image Gently campaign provides specific guidance on optimising diagnostic CT for paediatric patients [48], based on which some IGRT vendors have developed “Image Gently” IGRT protocols for paediatric patients [49]. However other vendors leave paediatric imaging optimisation entirely to the end user. Without clear guidelines for end-user IGRT optimisation, absent vendor-provided, paediatric-specific protocols may contribute to reluctance to implement CBCT in paediatric patients. Furthermore, ad hoc optimisation without structured optimisation workflows may result in excessive dose lowering, leading to image verification uncertainties and repeated scans, thereby defeating the purpose of IGRT imaging optimisation. As a result, some recommend an individualised approach based on the patient’s age, body size, immobilisation and radiotherapy technique [50].

Optimisation approach for paediatric IGRT.

The use of optimised, low-dose CBCT protocols for paediatric patients has been documented in the literature since 2014. Studies reveal diverse optimisation approaches employed, including prospective clinical optimisation using patient images, in silico optimisation in simulated patient images, and phantom-based optimisations. Østergaard et al. reviewed the literature on clinical optimisation of paediatric-specific CBCT protocols for IGRT and identified seven relevant papers [41]. The review found that optimised low-dose CBCT protocols existed

for both CNS and abdominal targets but were infrequently applied clinically [41]. A large North American survey found that most clinics aiming to optimise paediatric IGRT practices reduced dose by lowering mAs/kVp, using low-dose protocols from vendors, or preferentially using kV over MV imaging [44], although others showed reducing CBCT projection angles effectively lowered dose as well [51]. Several researchers recommended optimising specific low-dose CBCT protocols based on the registration target (i.e., bony or soft-tissue anatomy) [52,53]. In silico evaluations [54,55] include a simulation of ultra-low dose CBCT for bony anatomy registration and another exploring the impact of motion-related artefacts in the abdomen on optimisation potential [54,55]. A phantom study determined that CBCT dose could be reduced to match the dose of a standard “full dose” 2D kV imaging pair while maintaining sufficient image quality for IGRT patient alignment [56]. This is an important consideration for paediatric patients, where 2D imaging may be favoured because of dose concerns despite CBCT’s superiority in addressing rotational setup errors and improved soft-tissue visualisation [56–59]. Therefore, paediatric protocol definition should consider the frequency and potentially combining CBCT and 2D imaging.

However, just as with adults, situations exist for which higher IGRT doses may be appropriate and warranted. Paediatric patients who receive treatments with high doses per fraction and steep dose gradients, e.g., in craniospinal irradiation [60] or proton beam therapy [61], may particularly benefit from daily image guidance to minimise the impact of setup (i.e., positioning and registration) errors on the dose distribution to the target volume.

Current guidelines

Several national and international bodies have published guidelines, recommendations, and consensus documents about the implementation of image guidance and “best practice” in IGRT [2,7,15,62–64]. Of note, specific recommendations are also available for distinct diagnoses [65,66] and paediatric cancer patients [67]. Lastly, the international commission on radiological protection task group 116 is currently working on providing guidance on radiological protection aspects in the use of imaging in radiotherapy [68].

In general, guidelines agreed that the use and frequency of x-ray-based images, as well as the choice of imaging modality (e.g., 2D vs 3D) should be justified, and the risk/benefit ratio should be considered. However, it is also recognised that this balance between risk and benefit is subjective and based on judgment of priority. Therefore, different clinicians or institutions may have different perceptions of the benefits of, for example, daily CBCT imaging, in a particular patient group or even in individual patients.

AAPM TG 180 specifies that imaging dose should be considered in the treatment planning process if the cumulative imaging dose is $> 5\%$ of the prescribed therapeutic dose, but does not specify how it should be accounted for [15]. It is also recognised that measuring imaging doses and comparing them to therapeutic dose distributions is non-trivial [69]. Guidance regarding typical CBCT dose levels are published [15,18] and can be used as a point of comparison, although relevance to local CBCT protocols must still be confirmed by measurements. In the UK, a joint report from the Royal College of Radiologists, the Society and College of Radiographers and the Institute of Physics and Engineering in Medicine mandates that “appropriate imaging protocols should be available for a range of sizes and ages”. While manufacturers provide some protocols based on size (“small pelvis” vs “large pelvis”), age-based protocols are, at present, missing [63].

Although managing an IGRT program is often described as a responsibility of the multi-disciplinary team (e.g., radiation oncologists, RTTs, medical physicists), optimising imaging protocols to minimise the dose while maintaining acceptable image quality for clinical use is considered to fall specifically under the responsibility of medical physicists [62,67]. However, little direction is provided in existing guidelines

as to how this imaging optimisation process should be performed. The sections that follow aim to address this need.

Practical advice for CBCT optimisation

IGRT optimisation can be a taxing task for busy radiotherapy departments. The staff resources and expertise required for a comprehensive imaging optimisation approach might be a deterrent for those departments that adopt the default manufacturer settings. Additionally, the perception amongst radiotherapy professionals that imaging doses are negligible when compared to therapeutic doses, and the still-emerging evidence of low-dose effects [70,71] can result in imaging optimisation projects being under-prioritised. Some centres already follow an ad-hoc approach, which involves optimising scans for individual patients between radiotherapy fractions. For example, after initial imaging with vendor-default settings and review of image quality, it may be appropriate to reduce exposure factors for smaller patients or increase exposure factors for larger patients (typically through the total mAs for the imaging event) for the next fraction. Optimisation can be continued iteratively through the course of treatment. With relatively small changes between fractions (of the order 10–20 % in terms of mAs), changes in image quality between individual fractions will be minimal (and may not even be noticed by a human observer). This can achieve potentially substantial dose reductions and/or image-quality improvements over the course of treatment. Whilst such an approach can be useful and recommended (especially when image quality from vendor-default settings is very poor for specific patients) issues can arise, for example, with dose justification if dose is to be increased.

During the ESTRO Physics Workshop, the members of the working group agreed that a systematic yet pragmatic approach for optimising IGRT imaging could help increase the number of radiotherapy departments that move from default settings into those that are optimised to local patient populations and needs. The members also discussed providing benchmark values such as reference dose levels or specific imaging protocol parameters, however, this was deemed beyond the scope of this publication. The group decided that a framework for optimisation that can be adapted and used by departments regardless of their local techniques, resources and patient population would be more appropriate rather than providing benchmark values. Other studies have already published benchmark values such as national reference dose levels [18], typical imaging doses [15], or example imaging protocols [22]. Fig. 2 provides a graphical overview of our proposed pragmatic approach to CBCT optimisation and the appendix contains a check-list template to encourage clinics to implement our workflow. The pragmatic approach comprises three essential phases: (1) protocol optimisation (2) clinical implementation (3) ongoing evaluation.

To facilitate progression through all three phases, we suggest every department establish a multidisciplinary IGRT team. The team should include, but may not be limited to, radiotherapy and imaging physicists (ideally Medical Physics Experts), RTTs and radiation oncologists. As AI use in image generation, processing, and registration increases, computer scientists/data architects will become increasingly important members to include in the team if possible. Lastly, continuous interaction and consultation with the manufacturer is advised to ensure the latest technological solutions are utilised. Equally the manufacturers should support flexible configurations and allow end users to tailor imaging protocols to local clinical needs and provide support when needed, rather than providing “black box” imaging solutions unable to be personalized to local needs. A periodically repeating procedure can be used to ensure continuous adoption of the new technological developments and updates of the applied protocols in the clinic. Although the multidisciplinary team will take a leading role in optimising and implementing protocols, establishing a systematic and robust approach for choosing modality, frequency, match method, and IGRT protocol for individual patients, the IGRT practices should be widely disseminated and agreed upon within the department. We stress here the importance

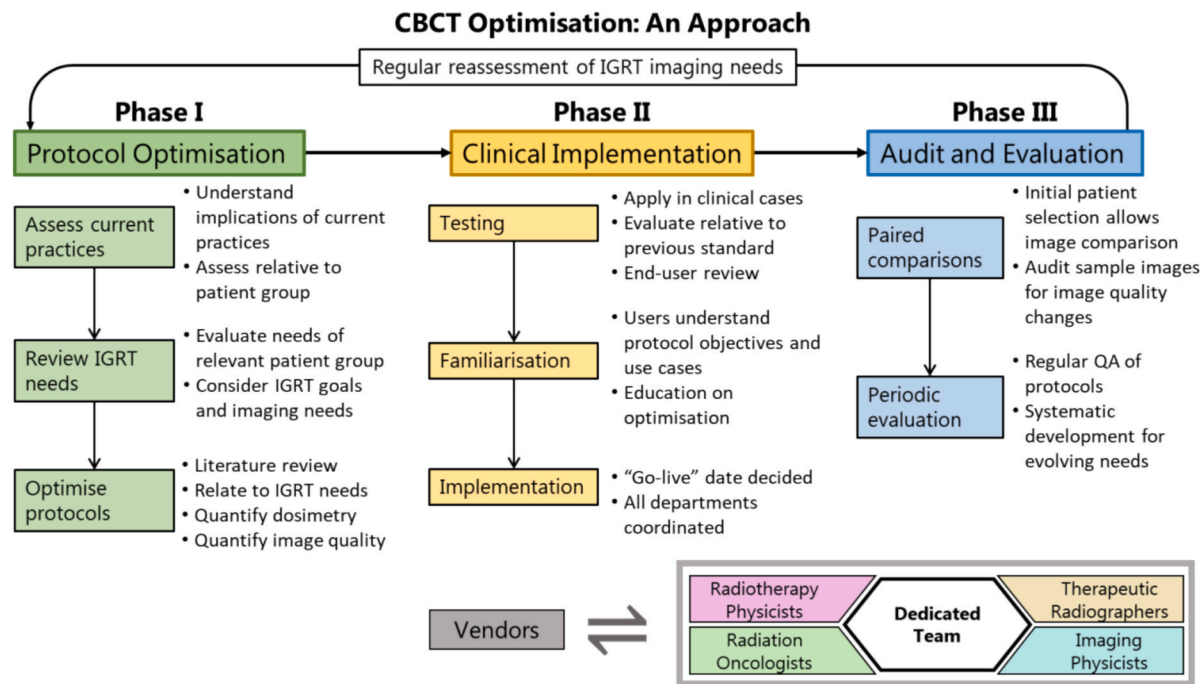


Fig. 2. Schematic overview of the proposed pragmatic approach to optimising cone-beam computed tomographic (CBCT) imaging protocols for the purposes of image-guided radiation therapy (IGRT). Abbreviations: QA = Quality Assurance.

of including RTTs and radiation oncologists in the IGRT imaging optimisation from the beginning and, importantly, in assessing image quality and its clinical and practical implications to avoid relying on quantitative indices, such as signal to noise ratio (SNR) or contrast to noise ratio (CNR), alone.

Phase I: Protocol Optimisation

The first phase of an IGRT imaging optimisation program involves optimising the imaging protocols themselves. We recommend a protocol optimisation procedure that comprises three primary steps:

Step 1: Assess current practices: Develop an understanding of the image-quality and dose implications of current practices. A good starting point is to prioritise image quality review for patients with clinical indications whose CBCT scans are often of poor quality (e.g. abdominal CBCT) and those who may be considered to represent the extremes of the local population. Even when image quality is deemed satisfactory, the team is encouraged to review whether further dose reduction can be achieved with acceptable image quality. Reviews should be organised by clinical indications (or groups of similar indications) so that optimal imaging techniques can be developed for specific applications (e.g. prostate, gynaecological, SRS).

- Image-quality review should apply robust and relevant standards for evaluation that should be agreed by the multidisciplinary IGRT team to evaluate the relevant aspects of image quality for the task. Evaluation may include subjective measures (e.g., grading image noise and/or quality of relevant clinical structures on an ordinal scale) and/or objective parameters (e.g., region-of-interest-based measures of CT numbers and noise). In all cases caution should be used when interpreting data (for example, averaging of ordinal-scale values should be avoided).
- Dose review should assess dose indices such as CTDIs and DLPs for each protocol and how doses accumulate over the fractions. Doses should be compared to national dose reference levels [18,72], if available, international reference levels [73–75], or published doses for the same manufacturer.

Step 2: Review local IGRT needs: Evaluate the image-quality needs

for each clinical indication reviewed in step 1. By way of example, the quality of imaging for particularly small patients and very large patients who are currently imaged on a single mode could be compared with those that may be considered more 'standard' sized. From this data, it is possible to identify priorities for the local patient population. A common example is where the image quality is poor on bariatric patients, and as a result the matching task may be compromised through the lack of visualisation of soft-tissue structures. Such poor soft-tissue visualisation would imply imaging optimisation is needed to improve image quality in this patient group. Conversely, if such an image quality review demonstrates that all patients achieve acceptable levels of image quality no matter their size, it is implied that those patients who are smaller could achieve the 'acceptable' standard of image quality with reduced exposure factors.

Step 3: Optimise Protocols: Optimise IGRT protocols to meet the needs identified in Step 2. There are several layers of complexity at which to perform imaging optimisation, depending on the available resources and expertise of the multidisciplinary team. Clinics and centres looking for a generalised optimisation approach to apply across groups of patients can take the following steps:

- **Identify relevant literature:** Conduct a literature review to identify the latest publications available on optimised imaging protocols for the centre's CBCT manufacturer, treatment techniques, and patient population. For example, Table 1 here or Table 1 in publication [41].
- **Assess relevant literature:** Evaluate the quality of the methodologies in the identified publications. How were the protocols developed and tested? Are there any audits on actual patients post implementation?
- **Identify Proposed Protocols:** There are two possible avenues for arriving at proposed protocols:
 - a. **Select relevant protocol(s) from the literature:** Assess the extent to which the protocols are appropriate for the local practice. The multidisciplinary team should consider similarities and differences between their practice and those represented in the literature regarding patient population (adults vs paediatric), radiotherapy techniques used locally (3D-CRT vs VMAT vs SABR/

SRS) and relevant imaging protocols, specific tumour sites, potential requirements for patient-size-specific protocols, etc. Protocols from the literature can be implemented as published, if optimal as they are, or the multidisciplinary team may make necessary modifications to maximize relevance to the local population and practice.

- b. **Develop imaging protocols locally:** If the available protocols from the literature fail to satisfy the local needs, the multidisciplinary team should develop new protocols. The procedure for identifying new, local imaging protocols might involve phantom imaging (e.g., RANDO, CATPHAN, paediatric phantoms) using phantoms relevant to the target patient population and making incremental changes on the default exposure parameters. Evaluation of impacts of modified exposure parameters on image quality should include quantitative (e.g., SNR, CNR, CT numbers) and qualitative (visual) image quality assessments. Input from the imaging physicist in this step is crucial. An example of such changes is provided in Table 2 to demonstrate how centres might reduce imaging dose while preserving imaging utility or increase dose to improve image quality, tailored to specific treatment requirements.
- **Quantify local dosimetry:** Measure radiation dose indices (e.g., CT dose index (CTDI), weighted CTDI (CTDI_w)) [76] for each proposed protocol to confirm local implementation is consistent with the reported doses and establish baseline dose magnitudes for ongoing quality assurance practices. Measurements using pencil ion chambers and CTDI PMMA phantoms are recommended. However, if this equipment is inaccessible locally, recent work by an international collaboration [36] offers an alternative measuring method. The approach uses standard Farmer chambers and slab phantoms (which are commonly available in radiotherapy departments) to estimate CBCT dose indices, with published correction factors to approximate CTDI_w values. Such methods may offer an accessible pathway to support dose assessment and optimisation in resource-limited settings.
- **Quantify image quality:** Validate and benchmark image quality via phantom imaging tests using the old and newly optimised protocols.
- **Generate proposal:** Choose protocols to propose for local implementation, being sure to make necessary modifications to maximize relevance to the local population and practice. Provide an estimate of the potential dose reductions/increases based on the published or measured information on protocol doses, acquisition times, patient populations, and any modifications made for local applicability. Note that a conversation with the clinicians and a thorough justification are crucial, especially for proposals that will increase imaging dose.

Phase II: Clinical Implementation

Step 4: Testing: Once the optimised protocols have been selected and radiation dose measurements and phantom imaging tests are

complete, the new protocols can be tested for a small number of patients on at least one of the linacs before wider implementation.

We recommend choosing at least 5 patients for each new protocol, being sure to include patients of various sizes for one-size-fits-all protocols. Additionally, patients who already have CBCT images taken (i.e., who are in the middle of their radiotherapy course) should be selected so the images taken with the new protocols can be compared to those acquired with the previous protocols for the same patient.

Members of the clinical team who can be considered “end users” specialised in IGRT should evaluate and compare image quality to that of the previous IGRT protocols online and offline. Ideally that end user should involve several independent reviewers to minimise bias. Although in many cases the reviewers will be RTTs (e.g., the RTT representative on the multidisciplinary IGRT imaging optimisation team), the most appropriate choice may depend on geographical region, legislation, or treatment site. Many examples in the literature describe straight-forward, effective, and efficient methods to score image quality [22,23,32,51,52,54] using a Likert scale or binary assessment of whether the image was useful for image guidance for a specific task.

Step 5: Familiarisation: An important step to full integration is communication to the full RTT team. All RTTs must be familiar with the names of the newly optimised IGRT imaging protocols, the objectives and intended uses of each one, and the robust methods for selecting the appropriate optimised protocol for each patient. Clinical implementation can also be used to educate the clinical team in the parameters that affect dose and raise awareness about the need for IGRT imaging optimisation and the importance of patient-appropriate imaging protocols.

Step 6: Implementation: When all protocols have passed the testing phase described above and the relevant end-users (e.g., RTTs) have received all necessary information and training, the new protocols can be implemented in all linacs in the department. A “go live” date should be agreed between RTTs and physics. Members from both teams should be present on the “go live” day.

Clinics and centres with the resources to do so should evaluate individual imaging doses and record them alongside the therapeutic doses. However, commercial solutions for estimating and recording imaging doses throughout treatment are currently lacking.

Phase III: Audit and Evaluation

Implementing newly optimised IGRT protocols in the middle of patient treatment courses will produce CBCT images acquired with both the old and new protocols for the same patients. Such paired image samples should be audited and compared to ensure the new protocols are free from unexpected declines in image quality or effects on RTTs’ ability to perform online image matching. A further audit at a later stage can be performed to evaluate the proportion of patients whose imaging doses were affected (i.e., increased or reduced from that of the old protocols).

Ideally, annual evaluation of CBCT protocols should be performed to ensure protocols are appropriately selected and unused protocols are addressed (i.e., removed if unnecessary, modified as needed, and

Table 2
Examples of optimised protocols and comparison with manufacturers’ default settings.

CBCT Protocols	kV	mA	ms	f/s	Gantry speed (°/S)	Trajectory	Number of projections	mAs	CTDI in Air (mGy)	Change in CTDI _{air} (%)
Head Protocols										
Vendor Default*	100	14	20	15	6	Half	500	140	6.2	–
Dose optimised [33]	100	10	15	15	6	Half	500	75	3.1	–50 %
Image quality optimised for SRS treatments [25]	100	30	20	15	6	Half	500	300	10.5	+70 %
Pelvis Protocols										
Vendor Default*	125	38	20	15	6	Full	900	684	42.8	–
Dose optimised [33]	125	25	10	15	6	Full	900	225	15.7	–63 %
Image quality optimised to reduce motion and metal artefacts [21]	125	38	20	15	3	Full	1800	1368	85.6	+100 %

Abbreviations: KV-Kilovoltage, mA-milliampere, ms-milliseconds, f/s-frames per second, CTDI-computed tomography dose index, mGy-miligray.

*Varian TrueBeam.

updated RTT communication and training as appropriate). Annual evaluation could include, but not be limited to, repeating Step 1 of the presented workflow. Consistent updates to procedures should aim to simplify protocol selection and QA requirements and incorporate new technological developments into existing protocols expeditiously.

Summary/conclusions

IGRT imaging optimisation is critical, particularly for paediatric patients who are more radiosensitive and typically survive longer than adults. Optimisation is a continuous process that needs to be evaluated regularly (e.g. annually or bi-annually) to ensure all available technological developments and current literature are fully utilised and that the used CBCT protocols continue to reflect current practice and local patient needs. The number of protocols and QA requirements should be balanced by the ease of the protocol selection process. Involvement of RTTs and imaging physicists in the whole process through a multidisciplinary approach is pivotal for successful implementation and clinically relevant changes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.radonc.2025.110958>.

Data availability

Data will be made available on request.

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