Radiography 26 (2020) S62–S68

Contents lists available at ScienceDirect

Radiography

journal homepage: www.elsevier.com/locate/radi

Strategies for dose reduction with specific clinical indications during computed tomography

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ARTICLE INFO

Article history:
Received 24 April 2020
Received in revised form
12 June 2020
Accepted 15 June 2020
Available online 15 July 2020

Keywords:
CT
Dose reduction
Cystic fibrosis
Crohn's disease

ABSTRACT

Increasing integration of computed tomography (CT) into routine patient care has escalated concerns regarding associated radiation exposure. Specific patient cohorts, particularly those with cystic fibrosis (CF) and Crohn's disease, have repeat exposures and thus have an increased risk of high lifetime cumulative effective dose exposures.

Thoracic CT is the gold standard imaging method in the diagnosis, assessment and management of pulmonary disease. In the setting of CF, CT demonstrates increased sensitivity compared with pulmonary function tests and chest radiography. Furthermore, in specific cases of Crohn's disease, CT demonstrates diagnostic superiority over magnetic resonance imaging (MRI) for radiological evaluation.

Low dose CT protocols have proven beneficial in the evaluation of CF, Crohn's disease and renal calculi, and in the follow up of testicular cancer patients. For individuals with chronic conditions warranting frequent radiological follow up, the focus must continue to be the incorporation of appropriate CT use into patient care. This is of particular importance for the paediatric population who are most susceptible to potential radiation induced malignancy.

CT technological developments continue to focus on radiation dose optimisation. This article aims to highlight these advancements, which prioritise the acquisition of diagnostically satisfactory images with the least amount of radiation possible.

Introduction

A significant and widespread increase in the utilisation of computed tomography (CT) has been evident in recent decades. In 2017, in excess of 6 million CT examinations were conducted across UK hospitals.[1]

Concerns regarding CT associated radiation exposure are heightening; compared with conventional diagnostic radiographs, CT results in exposure to much higher radiation doses. A routine thoracic CT can potentially deliver an effective dose that is 50-fold higher than that associated with a standard chest radiograph.[2] Additionally, the potential inherent radiation dose associated with CT has increased as faster image acquisition speeds facilitate vascular and multi-phase examinations. Consequently, it can be surmised that the increased reliance on CT imaging has resulted in a concomitant rise in medical exposure to ionising radiation in the population.[3] Concurrent with the increasing use of CT, advances in CT technology have facilitated significant reductions in radiation exposure during individual examinations. Dose optimisation aims to produce a diagnostically satisfactory image while keeping the radiation dose as low as reasonably achievable.

This review article provides a brief overview of patient cohorts at heightened risk of excessive radiation exposures. Additionally, various CT dose reduction strategies applicable to these specific groups will be discussed, highlighting the potential clinical benefits of implementing such strategies, based on experience at our centre over the past decade.

Concerns regarding an increasing reliance on CT imaging

Invaluable in the diagnosis of complex medical issues, CT is widely accepted as one of the more momentous recent advances in medicine, with integration into routine patient care responsible for

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https://doi.org/10.1016/j.radi.2020.06.012

List of abbreviations

AEC	Automatic exposure control
ALARA	As low as reasonably achievable
ASIR	Adaptive statistical iterative reconstruction
ATCM	Automatic tube current modulation
CD	Crohn's disease
CED	Cumulative effective dose
CF	Cystic fibrosis
CT	Computed tomography
CT-AP	Abdominopelvic CT
CT-KUB	CT kidneys, ureters, bladder
CTDI	CT dose index
DLP	Dose length product
ED	Effective dose
FBP	Filtered back projection
ICRP	International Commission on Radiological Protection
IR	Iterative reconstruction
kV	Kilovolt
MBIR	Model based iterative reconstruction
MRI	Magnetic resonance imaging
Sv	Sievert
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
US	United States

improved patient outcomes. Whilst CT use in the emergency department setting has risen across the United States (US),[4] this has been disproportionate to the increase in patient attendances at emergency departments.[5] Furthermore, a corresponding variation in diagnostic yield has not been demonstrated. Increasing availability of CT resources may be contributing to a supply-induced demand, resulting in increased utilisation of CT, without a demonstrable increase in quality of patient care.

CT remains the largest contributor to medical radiation exposure, accounting for almost 50% of the collective effective dose. This is concerning; as a stochastic process, the probability of radiation induced carcinogenesis increases with escalating radiation dose exposures. Compared with adults, children are much more susceptible to these stochastic effects; their tissues demonstrate increased radiosensitivity due to rapid cell division and growth.

Health information

Quantification of medical radiation associated risk is difficult; several clinical studies have attempted quantification of risk of malignancy from CT radiation exposure.[6,7] However, precise calculation of both the probability of harm and potential severity of that harm is almost impossible. Available data regarding radiation induced malignancy is population based as opposed to individual calculated risk. Given the latency of radiation induced cancer is 10–20 years, effects of radiation exposure may not become apparent for decades, if at all.

Whilst published estimates of radiation exposure associated cancer risk include the induction of 125 breast cancers per 100,000 women screened between ages 40 and 74 years,[8] and a 1.8% increase in lung cancer incidence if 50% of the population between the ages of 50 and 75 years were screened annually with CT for lung cancer, estimation of diagnostic range ionizing radiation exposure associated risk remains controversial.[9]

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has reported uncertainty in relation to the health effects of low dose radiation. At doses less than 100 mSv, the risk of radiation induced malignancy is thought to be too small to be distinguishable from other risk factors for cancer development.[10,11] However, a retrospective cohort study, evaluating the risk of leukaemia and brain tumours associated with CT imaging performed in paediatric patients, noted that in the 10 years following first CT scan undertaken in patients younger than 10 years, one excess case of leukaemia and one excess case of a brain tumour per 10,000 head CT scans occurred.[6] Recently, flow cytometry techniques have facilitated assessment of biomarkers of radiation damage at diagnostic levels as low as 7.5 mSv.[12] This data verifies that damage is occurring, and being repaired, in most individuals. However, it also demonstrates that individuals with damage or mutation to their repair pathways do not repair the damage caused by low dose radiation. This reinforces the need for radiation doses to be “personalised” or appropriate to the individual, rather than the average patient.

Reports projecting cancer risk associated with ever increasing CT use have resulted in a heightened awareness among patients regarding potential adverse health outcomes secondary to ionizing radiation exposure. This is compounded by the relatively high volume of inaccurate information, related to CT associated radiation exposure, to be found on Internet searches; an assessment of Internet searches for details regarding radiation safety noted that information provided on webpages is accurate in just two thirds of cases.[13]

Cohorts with potential for excessive radiation exposures

Approximately 50% of total population radiation dose exposure is now accounted for by medical imaging[14]; CT is responsible for approximately 60% of total dose exposure associated with medical imaging.[15] Cumulative effective dose (CED), a measure of the total radiation dose incurred by a patient over time secondary to repeated exposures during diagnostic imaging, is of particular concern among younger patient cohorts; associated risks are deemed higher once CT is performed on younger patients.

Specific patient cohorts are acknowledged as being at increased risk for high lifetime CED. These include patients with testicular cancer,[16] cystic fibrosis (CF),[17] inflammatory bowel disease (in particular Crohn's disease (CD) patients),[18] lymphoma[19] and end-stage kidney disease,[20] in addition to trauma patients, and patients admitted within intensive care facilities for extended periods of time.[21]

Of heightened significance is that age at the time of first radiation exposure is now accepted as an independent risk factor for subsequent cancer mortality. For patients with CF and CD, this is of particular relevance as first clinical presentation typically occurs within the paediatric setting.

CF patients have CEDs in excess of the general population, with a 6-fold increase in the use of CT scanning for these patients reported.[17] These individuals will proceed to an average of 3.2 thoracic CT scans (range 0–13) during their lifetime.[22] Mean annual effective dose for a cohort of paediatric patients with CF has been recorded as 0.15 mSv/year; CED between birth and 18 years of age is estimated at 3.5 mSv.[23] Furthermore, average age at first CT Thorax has reduced significantly in recent years, from 20 years for patients born pre 1980, to 1.9 years for patients born post 1997.[22] In view of their multisystem disorder, abdominal imaging contributes to a significant proportion of total CED exposure for CF patients; in

excess of 40% of all radiologic imaging may be directed at the abdominopelvic region.[17] Traditionally, diagnostic abdominal CT imaging necessitates much higher radiation doses compared with the thoracic equivalent.

Consequently, patients with inflammatory bowel disease, in particular CD, are also at increased risk of exposure to high levels of radiation associated with their diagnostic imaging studies. High levels of both annual CED and total CED are independently associated with CD, with values of >9.6 mSv/annum and >30.8 mSv, respectively.[24] Most CD patients receive their diagnosis between the ages of 15 and 40 years, with one large US epidemiological study reporting a median age at diagnosis of 29.5 years.[25] This young age profile at diagnosis, in addition to, often, decades of active disease mean CD patients frequently proceed to repeated abdominal imaging. CD patients with penetrating and upper gastrointestinal tract disease, along with those warranting treatment with intravenous steroids and biologics, all have associated increased CEDs.[18]

Testicular cancer is the most common cancer affecting men aged between 14 and 44 years[26]; CT, endorsed by standard international protocols, is essential in staging and surveillance. However, CT accounts for up to 98.3% of CED amongst this patient group, with a median CED of 125.1 mSv reported.[16]

CT dose optimisation strategies

In general terms, when selecting a radiological investigation or procedure, the consequent radiation exposure must always be considered. As highlighted in the “Image wisely” and “Image gently” campaigns,[27,28] a three-tiered approach to radiation protection is beneficial:

- the as low as reasonably achievable (ALARA) principle;
- justification of the imaging procedure;
- dose limitation.

Essentially, the optimal method for reducing radiation dose is to avoid unwarranted CT imaging, and instead utilise alternative imaging modalities in an effort to limit, or even eliminate, radiation exposure. With particular relevance to the paediatric population, this may be aided by the provision of imaging consultations to advise referring physicians on the most appropriate diagnostic imaging pathway.[29]

CT associated patient radiation exposure is estimated using 3 main metrics: volume CT dose index $(CTDI)_{vol}$ represents the radiation dose output from the scanner; dose-length product (DLP) represents the radiation dose over the total scan; and effective dose (ED) measures the equivalent whole-body dose which would have the same risk of the biologic effect. ED, expressed as the millisievert (mSv), is formulated by the summation of absorbed doses to individual organs weighted for their radiation sensitivity.

In cases where CT is deemed necessary on clinical grounds, it must be considered that CT associated radiation dose is dependent on a number of scanning parameters including: tube current, tube voltage, scanning length, table pitch, gantry rotation time, collimation, table speed and shielding (Table 1).

Image noise, a significant predictor of image quality, is inversely related to X-ray beam energy; though radiation dose can be reduced directly through alterations to tube current and tube voltage, this impacts negatively on image noise. Tube current reduction is the most accessible method of reducing CT radiation dose, though this process again increases image noise. Potentially, a 50% reduction in radiation dose exposure can be achieved through a 50% reduction in tube current.[30] Additionally, tube voltage affects both image noise and tissue contrast by virtue of the quantity of radiation administered; radiation output is proportional to the square of tube voltage. Consequently, even minimal decreases in tube voltage can aid significant dose reduction.[31] When imaging paediatric patients, it is important that weight-based protocols are followed; smaller patients may necessitate a proportional increase in tube current to balance their relative inherent lack of soft-tissue contrast.

Radiation dose exposure and image noise are further affected by patient positioning relative to the isocenter. Optimisation of image quality and radiation dose may be achieved in part by patient positioning at the isocenter of the CT gantry. As the complexity of CT examinations increases, so too does the potential for centering error; isocenter misalignment is greater during CT colonography compared with abdominopelvic CT (CT-AP) or CT kidneys, ureters, bladder (CT-KUB).[32]

Patient centering within the CT scanner is classically achieved through manual adjustment of both the patient and table position by the radiographer, with the assistance of laser guides. However, in spite of these laser beams facilitating visual assessment of the central positioning of patients, the technique does demonstrate variability between users; patient positioning at a non-ideal table height is not infrequent. As a means of improving table height selection, body contour detection has gained notable support in recent times; 3D cameras for body contour detection have been demonstrated to improve the accuracy of patient positioning compared with manual positioning.[33]

CT filters aim to reduce those soft X-rays which do not contribute to development of a diagnostic image, in spite of constituting a degree of absorbed ionising radiation.[34] Bowtie filters, a type of CT filter, harden the X-ray beam by removal of those low energy X-rays. They further concentrate the X-rays in the central aspect of the scanned anatomy, resulting in increased image quality and a reduction in surface dose of 50% when compared with flat filters. Given the elliptical body shape of most paediatric patients, these Bowtie filters offer significant dose reduction potential for the paediatric population.

Furthermore, the use of shielding during CT examinations has gained support as a means of dose reduction. Particularly targeted at protecting superficial organs, shielding materials such as lead and bismuth potentially attenuate the primary X-ray beam by up to 50% and 60% for the eye lens and breast, respectively.[35] The shielding of radiation transmission requires balance; the reduction of direct radiation exposure to the thyroid, eyes, gonads and breast tissue must not compromise the generation of diagnostically satisfactory images.

Advances in CT technologies aimed at dose optimisation

Developments in CT technology are focused on reducing radiation exposure as low as reasonably achievable, whilst maintaining diagnostic yield; recent advances have yielded significant reductions in radiation dose exposure in many clinical settings. Though any reduction in CT radiation dose is to be encouraged, limitations include increased image noise with secondary reduced image quality. This must be compensated for, if a detrimental effect on image quality, resulting in a non-diagnostic imaging study, is to be avoided.

Automatic tube current modulation (ATCM), a type of automatic exposure control (AEC), works on the basis that pixel noise on CT scanning is attributable to quantum (random) noise in the image projections. ATCM aims to maintain constant CT image quality, with a reduced radiation dose exposure, through automatic tube current adjustment in various planes according to the size and attenuation of the imaged body area. Whilst maintaining image quality, ATCM

Table 1
Effect of manipulation of scanning parameters on overall radiation dose exposure.

Scanning parameter	Effect on radiation dose
Tube current	Increased with higher tube current
Scan length	Increased with lengthening of scan range
Pitch	Decreased with higher pitch (at matched tube current)
Gantry rotation time	Decreased with faster gantry rotation
Collimation	Increased with thinner collimation
Distance of X-ray tube to CT isocenter	Decreased with optimal patient centering

has facilitated dose reductions of 31% and 21% for arterial and portal phase CT imaging of the abdomen, respectively.[36]

As a dose reduction strategy, adaptive section collimation offers significant potential for very young children. Most effective in scan ranges less than 12 cm, it reduces radiation exposure due to over-scanning; dose savings of up to 38% have been reported.[37]

Although bismuth shielding offers a mechanism for dose reduction to specific radiosensitive organs included in the field of view, organ-based dose modulation systems offer further potential to reduce the radiation exposure to superficially located organs. The technique exposes centrally located viscera to a constant radiation dose, thereby maintaining image quality, while those organs sited superficially are subject to a reduced radiation exposure within the prescribed 120° radial arc. Utilisation of an organ-based dose modulation system (liver dose right index) has demonstrated a statistically signficant reduction in radiation dose exposure to the breast and pelvic area, compared with standard AEC.[38]

Whilst standard CT scanners reconstruct images using filtered back projection (FBP), algorithms utilising iterative reconstruction (IR) have been produced to reconstruct image data using a system of models to improve image noise. IR isolates noise from CT images obtained at reduced exposure, maintaining image quality and interpretability, thus producing considerable radiation dose reduction whilst preserving satisfactory image quality, when compared with traditional FBP.

IR techniques significantly decrease subjective and quantitative image noise on both standard and reduced dose thoracic CT. Dose reductions of up to 63.8% for thoracic CT in paediatric patients can be achieved using adaptive statistical iterative reconstruction (ASIR) (GE Healthcare, MI, USA), without significantly compromising image quality.[39]

More advanced forms of IR include model-based iterative reconstruction (MBIR), a type of “pure” IR. Pure IR results in high quality images, with potential for dose reductions in excess of 80%.[40] MBIR facilitates ultra-low dose thoracic imaging, with maintenance of image quality, at doses approaching that of a chest radiograph.[41,42]

CT dose optimisation research strategies: effects on radiation exposure

Our centre has developed various low dose CT research protocols for use when imaging individuals from the above mentioned patient cohorts. Furthermore, for select groups, namely patients with CF, these low dose protocols have now been adopted into routine clinical practise within our department.

An increased understanding of the aetiology of CF lung disease confirms that even asymptomatic CF infants may have irreversible pulmonary pathology. Consequently, early diagnosis and surveillance of pulmonary disease is important for the preservation of lung parenchyma and to optimise long term outcomes. Despite the radiation doses incurred, CT is a vital imaging tool for CF patients, demonstrating increased sensitivity compared with pulmonary function tests and chest radiography.[43,44] As such, there is an ongoing onus to minimise radiation exposure, whilst maintaining diagnostic quality images.

Secondary to the high inherent contrast and low radiation absorption of the lung, thoracic CT is particularly suited to dose optimisation protocols. Low dose thin-section CT protocols for paediatric CF patients can be conducted at a mean effective dose of <0.02 mSv.[45] In comparing protocols with section thickness of 0.5 mm and 1 mm, both demonstrate *almost excellent* diagnostic acceptability and delineation of bronchovascular structures. Both protocols also demonstrate *excellent* correlation with chest radiograph findings. Further published reports have confirmed an effective dose reduction of 26% in this patient cohort following the implementation of thin-section protocols, without any compromise in image quality.[46] Therefore, low dose thin-section CT, performed at an effective dose approaching that of a chest radiograph, offers an alternative, high-yield imaging option for paediatric CF patients.

Iterative reconstruction (IR) offers further potential for CT dose optimisation in CF; when utilised with thoracic imaging in CF patients, IR facilitates contiguous/spiral chest imaging at chest radiography doses. ASIR reconstructed thoracic CT images can remain diagnostically satisfactory when obtained at 40 mAs/3.5 mGy.[47]

ASIR has also demonstrated potential in abdominal imaging (Table 2). It can facilitate acquisition of diagnostically acceptable low dose CT images of the urinary tract, at radiation dose exposures approaching that of an abdominal radiograph.[48] With a mean effective dose of 0.48 mSv, low dose CT, reconstructed with 70% ASIR, demonstrates a sensitivity and specificity of 87% and 100%, respectively, for the detection of renal calculi >3 mm. Of note, the fixed tube current low dose CT protocols demonstrate a reduction in DLP with increasing patient BMI. This compares with the statistically significant increase in DLP noted when patients with increasing BMI proceeded to conventional dose CT imaging.

Surveillance CT remains the standard of care following a diagnosis of testicular cancer; it is critical in the identification of recurrent disease, such that it may be treated with curative intent. Whilst surveillance recommendations vary between jurisdictions, the majority of patients necessitate multiple abdominopelvic CT examinations over the course of 5–10 follow-up years.[49]

MBIR has facilitated significant reductions in the radiation dose associated with testicular cancer surveillance CT scans. Our centre has demonstrated a radiation dose reduction of 67.1% with these image reconstructions, whilst maintaining diagnostic accuracy.[50] A cohort of sixteen patients, with stage I or II testicular cancer, proceeded to low dose CT acquisition, subsequently reconstructed with MBIR; all images were comparable, if not superior, to conventional dose imaging investigations in terms of quantitative image analysis. All low dose images acquired demonstrated complete *gold standard* correlation with the conventional dose CT images.

Additionally, MBIR has proven feasible as an option for the imaging of patients presenting with acute abdominal pain.[51] In demonstrating a 74.7% mean reduction in radiation dose, MBIR offers a viable dose reduction strategy for this patient group. From a cohort of fifty-seven patients, no difference in the sensitivity for primary findings was recorded between the low dose images

Table 2
Overview of low dose CT imaging studies undertaken at our institution. The iterative reconstruction algorithms utilised for investigation of a particular pathology are presented. Subject age, DLP and ED are presented as means ± standard deviation. Dose reductions facilitated by these low dose CT protocols compared with conventional dose CT studies are presented as ED or DLP as determined by published study data.

CT image reconstruction algorithm	Pathology	Subject age	DLP	ED	Dose reduction
ASIR	Renal calculi[48]	45.2 ± 16.3 years	34.18 ± 5.3 mGy.cm	0.48 ± 0.07 mSv	82.9 ± 8.0% (DLP)
ASIR	CD (CT-AP)[54]	37 ± 13.4 years	87.0 ± 56.2 mGy.cm	1.26 ± 0.8 mSv	73.6 ± 2.6% (DLP)
MBIR	Testicular cancer (CT-AP)[50]	35.6 ± 7.4 years	128 ± 38 mGy.cm	1.9 ± 0.6 mSv	67.1 ± 4.0% (DLP)
MBIR	Acute abdomen[51]	56.5 ± 8 years	158.5 ± 118.6 mGy.cm	2.38 ± 1.78 mSv	74.7% (ED)
MBIR	CD (CT enterography)[52]	38.5 ± 12.98 years	107.60 ± 78.7 mGy.cm	1.61 ± 1.18 mSv	74.7% (ED)
MBIR	CD (CT-AP)[55]	37.8 ± 13.7 years	88 ± 58 mGy.cm	1.27 ± 0.87 mSv	71.4 ± 2.4% (DLP)

CD – Crohn's disease; CT-AP – abdominopelvic CT; DLP – dose length product; ED – effective dose.

reconstructed with MBIR and the standard dose images, barring a single case of enteritis.

Compared with hybrid IR (combined filtered back projection and ASIR), MBIR yields superior images in terms of subjective and objective parameters for conventional dose CT enterography studies.[52] Of increased significance, for low dose CT enterography reconstructed with MBIR, the acquired images are at least comparable to, if not superior to, images resulting from conventional CT protocols.[53] These scans may be conducted with an average 74.7% reduction in radiation dose exposure. Significantly, the detection of complications of CD, in addition to an assessment of overall grade of CD activity, are comparable when evaluated with both low dose and conventional dose CT.

CT facilitates detailed detection of both intestinal and extra-intestinal manifestations and complications of CD; it is frequently conducted in the acute setting when there are clinical concerns regarding extramural complications, including abscess and perforation. Although MRI and enterography provide superior contrast resolution, and bowel wall and mucosal enhancement depiction, MRI is not optimal for all patients with CD.

The advent of hybrid IR triggered the development of protocols to guide low dose CT imaging of CD patients. CT-AP examinations conducted for reconstruction with a combination of filtered back projection and ASIR were noted to yield a mean effective dose of 1.3 mSv.[54] This represented a 73.6% reduction in mean radiation dose, compared with an effective dose of 4.7 mSv for conventional CT-AP imaging. Furthermore, from a clinical perspective, detection of extra-luminal complications was demonstrated to be comparable between low dose and conventional dose abdominopelvic CT.

In more recent times, MBIR has proven of further benefit for CT-AP dose reduction strategies in CD patients. In demonstrating perfect clinical agreement with standard dose CT-AP for the detection of extramural complications, low dose CT-AP protocols, reconstructed with pure IR, show promise as an alternative imaging option for the assessment of active CD.[55]

Low dose protocol inclusion into routine practise and future developments

In view of cumulative radiation exposure, the frequent imaging required in CF patients is a concern. Thoracic imaging typically commences during infancy, as the earliest CF radiological changes, mucous plugging, can be detected with CT imaging. Although CF is a life limiting disease and therefore the risk of radiation induced malignancy is reduced, life expectancy for CF patients continues to improve.[56] Median age of death from CF is rising, with an increase of 0.543 life years per year across the US, England and Wales between 1972 and 2009. As such, there is an ongoing requirement, supported by considerable academic and industry drive, to reduce radiation exposure incurred by patients undergoing CT, without sacrificing image quality and diagnostic accuracy.

Ireland has the highest worldwide incidence of CF[57]; prevalence of the *G551D* mutation in patients at our CF centre is 23%.[58] Ivacaftor (Kalydeco; Vertex Pharmaceuticals, MA, USA) was the first disease modifying drug in CF[59]; in Ireland, ivacaftor is now available for children from 1 year of age. Approved for use in CF patients with the *G551D* mutation, ivacaftor improves lung function, reduces sweat chloride levels and facilitates weight gain.[60] We have previously reported improvements in the severity of CF lung disease, using ultra-low dose CT (at a mean effective radiation dose of

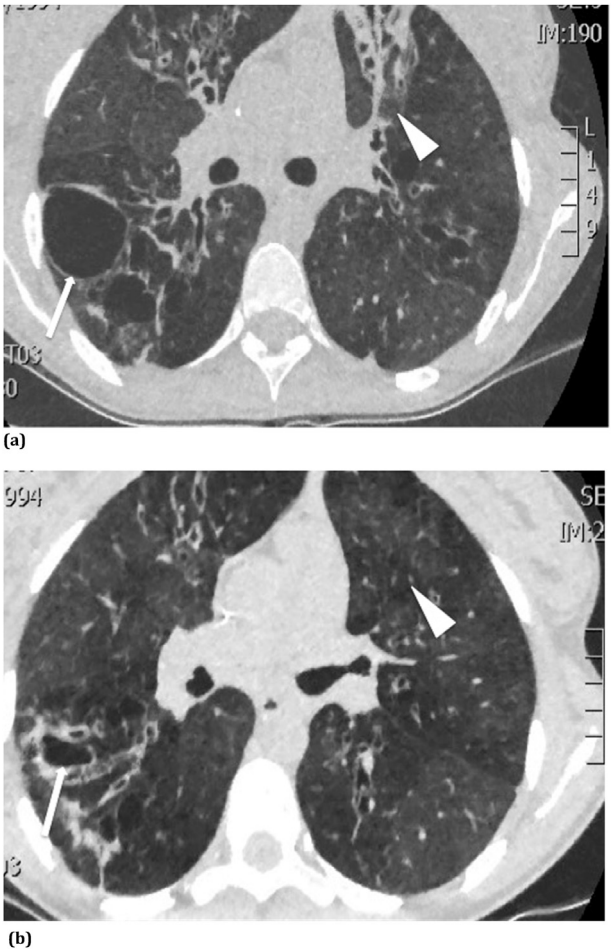

Figure 1. Ultra-low dose CT images in a female CF patient, aged 22 years. Total examination dose length product of 5.75 mGy-cm. CT axial section **a** prior to commencing treatment with ivacaftor (Kalydeco; Vertex Pharmaceuticals, MA, USA), demonstrating right lower lobe cystic lung changes (arrow) and extensive left upper lobe bronchial wall thickening (arrowhead); and **b** following six months of treatment with ivacaftor, a dramatic improvement in the severity of both airway thickening and cystic lung pathology is evident.

0.08 mSv) for follow up imaging, post initiation of ivacaftor[58] (Fig. 1).

All patients on treatment regimens with ivacaftor at our centre proceed to ultra-low dose CT imaging (conducted at radiation dose exposures approaching that of a standard chest radiograph) at scheduled, routine intervals, in addition to clinical and respiratory status assessments. The diagnostic acceptability of acquired ultra-low dose CT images has frequently proven invaluable in clinical practise. In cases of acute clinical deterioration, those recent CT images obtained at baseline respiratory status can be compared with newly acquired CT images, thus providing far superior comparative detail of acute pathology than review of a prior chest radiograph.

Employed for radiological follow up of CF patients, the volumetric low dose CT protocol is conducted with the following parameters: tube voltage: 80 kV; tube current: 20 mA; gantry rotation time: 0.4 s; pitch factor: 1.375; and FOV of 32 cm. Scanning is performed at end-inspiration from the lung apices to lung bases, to include the costophrenic recesses. Acquired at a slice thickness of 0.625 mm, images are reconstructed at a final slice thickness of 3 mm with MBIR in axial, coronal and sagittal planes.

With children most susceptible to potential radiation induced malignancy, the requirement to justify CT imaging and the need to use the lowest radiation dose achievable has never been greater. This is particularly relevant across the paediatric CF population, due to early illness onset and an increased risk of high cumulative radiation exposure throughout their lifelong illness. CT facilitates demonstration of early CF changes, including mucous plugging and bronchiectasis, at an earlier point than those abnormalities detected by pulmonary function tests and chest radiography; prompt diagnosis enables timely initiation of therapeutic interventions. Additionally, both progression of CF pulmonary disease and any improvements following therapeutic interventions can be accurately assessed with CT; timely adaptation of treatment regimens assists with the ultimate aim of limiting disease progression. As such, modified low dose CT protocols must be considered for the paediatric CF cohort.[61] An approval to adopt the ultra-low dose CT protocol into routine practise for the imaging of paediatric CF patients at our centre has recently been granted by the local ethics board; formal results will be published in due course.

Conclusion

Certain patient cohorts, namely those with CF and CD, essentially require lifelong radiological follow-up. CT has an important role in both disease surveillance and monitoring treatment response. CT is also crucially important in the assessment of acute flares of these disease states, presenting as an abrupt deterioration in clinical status.

Consequently, control of cumulative radiation exposure is now of utmost importance. Development and implementation of CT dose reduction strategies and protocols is essential. In utilising the lowest radiation dose possible, the beneficial effects of CT can be maintained, whilst the potential for undesired ill effects are minimised.

As outlined, a number of clinical conditions are suited to low dose CT imaging protocols. In particular, low dose CT is an appropriate imaging option for accurate evaluation of pathological changes in the CF lung, even at doses approaching that of a chest radiograph. The diagnostic quality of these images has resulted in successful implementation of the ultra-low dose protocols for routine radiological follow up of CF patients.

Conflict of interest statement

All authors confirm no conflict of interest.

Acknowledgements

This review article did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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