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Review Paper

Image quality in CT: From physical measurements to model observers

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ABSTRACT

Evaluation of image quality (IQ) in Computed Tomography (CT) is important to ensure that diagnostic questions are correctly answered, whilst keeping radiation dose to the patient as low as is reasonably possible. The assessment of individual aspects of IQ is already a key component of routine quality control of medical x-ray devices. These values together with standard dose indicators can be used to give rise to 'figures of merit' (FOM) to characterise the dose efficiency of the CT scanners operating in certain modes. The demand for clinically relevant IQ characterisation has naturally increased with the development of CT technology (detectors efficiency, image reconstruction and processing), resulting in the adaptation and evolution of assessment methods. The purpose of this review is to present the spectrum of various methods that have been used to characterise image quality in CT: from objective measurements of physical parameters to clinically task-based approaches (i.e. model observer (MO) approach) including pure human observer approach. When combined together with a dose indicator, a generalised dose efficiency index can be explored in a framework of system and patient dose optimisation. We will focus on the IQ methodologies that are required for dealing with standard reconstruction, but also for iterative reconstruction algorithms. With this concept the previously used FOM will be presented with a proposal to update them in order to make them relevant and up to date with technological progress. The MO that objectively assesses IQ for clinically relevant tasks represents the most promising method in terms of radiologist sensitivity performance and therefore of most relevance in the clinical environment.

Introduction

Diagnostic x-rays contribute to nearly 50% of the total annual collective effective dose of radiations from man-made and natural sources to the general population in western countries; computed tomography (CT) is the largest single source of this medical exposure.

The contribution of CT to collective dose has significantly increased in recent years and a considerable effort is required to control this trend and ensure that the benefits from the use of this technology outweigh the risks [1]. For example, in 2007–2008 the average dose per inhabitant, due to CT, was about 0.8 mSv in France and Switzerland, and about 0.7 mSv in Germany (as part of an average for all x-ray imaging of about 1.2 mSv and 1.7 mSv, respectively) [2–4]. An update of the French and German data showed that in 2012 the contribution of CT exposure had increased to approximately 1.15 mSv, with a similar increase shown in the last Swiss survey performed for 2013 [5].

In this context the radiation protection requirements in diagnostic radiology (justification of the examination and optimisation of the imaging protocol) need to be re-enforced. Justifying a CT scan is a clinical consideration and therefore will not be addressed in this work. However, the optimisation of a CT examination is achieved when image quality enables the clinical question to be answered whilst keeping patient radiation dose as low as reasonably possible. For this purpose the clinical question needs to be formulated as concretely as possible to enable a clear description of the image quality level required. To achieve this, appropriate and clinically

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relevant image quality parameters and radiation dose indices must be defined, described, and used. This paper concentrates on image quality parameters.

The first step of the optimisation process should ensure that x-ray conversion into image information is performed as efficiently as possible. In projection radiology such as radiology or mammography one can use the DQE (Detective Quantum Efficiency as described in IEC 62220-1/2) as a global figure of merit. Unfortunately, due to the geometry and data processing required for CT, the use of such a quantity is not feasible. In general, one will assess the amount of radiation required to achieve a certain level of image quality. As a surrogate of the radiation received by the detector one uses the standardised CT dose index ($CTDI_{vol}$). This quantity represents the average dose delivered in PMMA phantoms of 16 and 32 cm in diameter and is related to the amount of noise present in an image. According to its definition $CTDI_{vol}$ is different from the actual average dose delivered in a slice of a patient, and the latter should be estimated using the Size Specific Dose Estimator (SSDE) proposed by the AAPM (American Association of Physics in Medicine) [6]. For a given $CTDI_{vol}$ level, image quality parameters are generally assessed using the signal detection theory that considers the imaging system linear and shift invariant.

The next step of the optimisation process should be done with the clinical applications in mind. Direct determination of clinical performance is, however, difficult, expensive, and time-consuming. Furthermore, the results in these studies can be strongly dependent on the patient sample and on the radiologists involved. As an alternative, one can assess image quality using task-oriented image quality criteria. They will necessarily be simplistic in comparison to the clinical situations but make it possible to predict the perception of simple structures within an image. The phantoms available for this type of study remain quite simple whilst trying to mimic important disease-related structures in actual patients. It is likely that 3D printing techniques will improve phantom and task realism in the future [7–9]. To seek optimisation, task-oriented image quality metrics could be studied as a function of $CTDI_{vol}$ or SSDE. Figure 1 summarises this optimisation process.

Part 1 of this review focuses on signal detection theory and summarises the methods used to assess image quality in an objective way. When CT images are reconstructed using the standard filtered back-projection (FBP), these methods are commonly used to characterise a CT unit. The objective image quality metrics assess separate aspects of the features of the image, and therefore need to be combined to give an overall representation of the image quality.

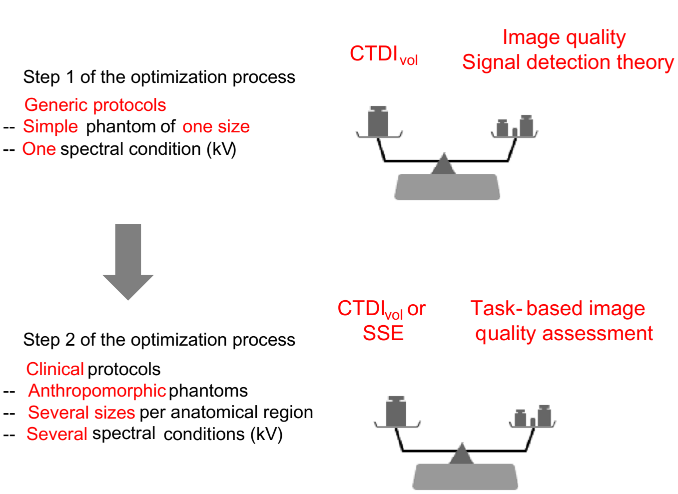

Figure 1. CT optimisation process in two steps: generic acquisition optimisation and clinical protocol optimisation.

To synthesise the information, and balance image quality with radiation doses, several figures of merit have been developed by combining image quality parameters such as the standard deviation in a region of interest (ROI) and the modulation transfer function (MTF). They were applied for specific clinical protocols to enable appropriate comparison of systems. This approach was quite useful during the development of CT technology, where performances between different units could vary drastically. These figures of merit can be based on simplified assumptions requiring caution in their interpretation. However it appears that the sensitivity of such methods is quite limited for newer systems, and, in addition, the effect of iterative reconstruction on the standard image quality parameters would mean that this approach would be difficult to implement.

Both clinical and phantom images can be assessed using the ROC paradigm or one of its derivatives (Localisation ROC, Free-response ROC). These methods give an accurate estimate of clinical image quality but, although carefully controlled measurements, they are still subjective because human observers are involved. These methods are time consuming and require large samples to obtain precise results. In spite of these limitations these methods can be used either by radiologists (when dealing with clinical images) or naïve observers when dealing with phantom images. To avoid the burden associated with ROC methods more simplified methods have been developed; for example, VGA (Visual Grading Analysis) in which image quality criteria can be used to give a relatively quick image quality assessment, without the explicit need for pathology or a task. Alternatively, phantom images can be assessed using the 2-AFC (two-alternative forced-choice) or M-AFC (multiple-alternative forced-choice) methods. Part 2 of this review discusses these methodologies, and these methods are used to validate the results produced by model observers presented in Part 3.

The introduction of iterative reconstruction in CT poses a new challenge in image quality assessment since most of the standard metrics presented in Part 1 cannot be used directly. In order to establish a bridge between radiologists and medical physicists, and therefore between clinical and physical image qualities, task related metrics can be used (even if the tasks are simplified versions of actual clinical tasks). Mathematical model observers are particularly suited to the routine image quality measurement of clinical protocols, with the results indicated to the user together with the standard dose report. Part 3 summarises the concepts behind these model observers, focusing on the anthropomorphic model observers that mimic human detection of simple targets in images, since the aim is to present tools for practical applications. The theory and description of the ideal observer can be found in the literature and a brief introduction to this model is done at the beginning of Part 3. Note that model observers can also be used when images are reconstructed with FBP. The inconvenience associated with the use of model observers is that they all lead to an overall outcome without the separation of the image quality parameters as with signal detection theory.

This paper is structured into three separate sections that provide an overview of the most common approaches taken when dealing with image quality in CT imaging. This structure is described in Fig. 2.

Traditional objective metrics

CT is a 3D imaging technique in which image quality assessment must be approached with some caution. Objective assessment of parameters that influence image quality is often made using physical metrics specified in either the spatial or spatial frequency domain. This duality is due to the fact that some features will produce overall responses which are independent of the location in the image, whereas other features will produce responses that are spatially correlated.