Image Reconstruction Techniques

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(Updated Sept. 2016)

Image reconstruction in CT is a mathematical process that generates tomographic images from X-ray projection data acquired at many different angles around the patient. Image reconstruction has fundamental impacts on image quality and therefore on radiation dose. For a given radiation dose it is desirable to reconstruct images with the lowest possible noise without sacrificing image accuracy and spatial resolution. Reconstructions that improve image quality can be translated into a reduction of radiation dose because images of the same quality can be reconstructed at lower dose.

Two major categories of reconstruction methods exist, analytical reconstruction and iterative reconstruction (IR). Let's focus on the analytical reconstruction methods at first. There are many types of analytical reconstruction methods. The most commonly used analytical reconstruction methods on commercial CT scanners are all in the form of filtered backprojection (FBP), which uses a 1D filter on the projection data before backprojecting (2D or 3D) the data onto the image space. The popularity of FBP-type of method is mainly because of its computational efficiency and numerical stability. Various FBP-type of analytical reconstruction methods were developed for different generations of CT data-acquisition geometries, from 2D parallel- and fan-beam CT in the 1970s and 1980s to helical and multi-slice CT with narrow detector coverage in late 1990s and early 2000s, and to multi-slice CT with a wide detector coverage (up to 320 detector rows and 16 cm width). 3D weighted FBP methods are generally adopted on scanners with more than 16 detector rows [1]. For a general introduction of the fundamental principles of CT image reconstruction, please refer to Chapter 3 in Kak and Slaney's book [2]. An introduction to reconstruction methods in helical and multi-slice CT can be found in Hsieh's book [3]. A review of analytical CT image reconstruction methods used on clinical CT scanners can be found in the article by Flohr, et al [4].

Users of clinical CT scanners usually have very limited control over the inner workings of the reconstruction method and are confined principally to adjusting various parameters that potentially affect image quality. The reconstruction kernel, also referred to as "filter" or "algorithm" by some CT vendors, is one of the most important parameters that affect the image quality. Generally speaking, there is a tradeoff between spatial resolution and noise for each kernel. A smoother kernel generates images with lower noise but with reduced spatial resolution. A sharper kernel generates images with higher spatial resolution, but increases the image noise.

The selection of reconstruction kernel should be based on specific clinical applications. For example, smooth kernels are usually used in brain exams or liver tumor assessment to reduce image noise and enhance low contrast detectability, whereas sharper kernels are usually used in exams to assess bony structures due to the clinical requirement of better spatial resolution.

Another important reconstruction parameter is slice thickness, which controls the spatial resolution in the longitudinal direction, influencing the tradeoffs among resolution, noise, and radiation dose. It is the responsibility of CT users to select the most appropriate reconstruction kernel and slice thickness for each clinical application so that the radiation dose can be minimized consistent with the image quality needed for the examination.

In addition to the conventional reconstruction kernels applied during image reconstruction, many noise reduction techniques, operating on image or projection data, are also available on commercial scanners or as third-party products. Many of these methods involve non-linear de-noising filters, some of which have been combined into the reconstruction kernels for the users' convenience. In some applications these methods perform quite well to reduce image noise while maintaining high-contrast resolution. If applied too aggressively, however, they tend to change the noise texture and sacrifice the low-contrast detectability in the image. Therefore, careful evaluation of these filters should be performed for each diagnostic task before they are deployed into wide-scale clinical usage.

Scanning techniques and image reconstructions in ECG-gated cardiac CT have a unique impact on image quality and radiation dose. Half-scan (or short-scan) reconstruction is typically used to obtain better temporal resolution. For the widely employed retrospective ECG-gated helical scan mode, the helical pitch is very low (~0.2 to 0.3) in order to avoid anatomical discontinuities between contiguous heart cycles. A significant dose reduction technique in helical cardiac scanning is ECG tube-current pulsing, which involves modulating the tube current down to 4% to 20% of the full tube current for phases that are of minimal interest. Prospective ECG-triggered sequential (or step-and-shoot) scans are a more dose-efficient scanning mode for cardiac CT, especially for single-phase studies. An overview of scanning and reconstruction techniques in cardiac CT can be found in an article by Flohr et al [5].

Different from analytical reconstruction methods, IR reconstructs images by iteratively optimizing an objective function, which typically consists of a data fidelity term and an edge-preserving regularization term [6]. The optimization process in IR involves iterations of forward projection and backprojection between image space and projection space. With the advances in computing technology, IR has become a very popular choice in routine CT practice because it has many advantages compared with conventional FBP techniques. Important physical factors including focal spot and detector geometry, photon statistics, X-ray beam spectrum, and scattering can be more accurately incorporated into IR, yielding lower image noise and higher spatial resolution compared with FBP. In addition, IR can reduce image artifacts such as beam hardening, windmill, and metal artifacts.

Due to the intrinsic difference in data handling between FBP and iterative reconstruction, images from IR may have a different appearance (e.g., noise texture) from those using FBP reconstruction. More importantly, the spatial resolution in a local region of IR-reconstructed images is highly dependent on the contrast and noise of the surrounding structures due to the non-linear regularization term and other factors during the optimization process [7]. Measurements on different commercial IR methods have demonstrated this contrast- and noise-dependency of spatial resolution [8,9]. Because of this dependency, the amount of potential radiation dose reduction allowable by IR is dependent on the diagnostic task since the contrast of the subject and the noise of the exam vary substantially in clinical exams [10]. For low-contrast detection tasks, several phantom and human observer studies on multiple commercial IR methods demonstrated that only marginal or a small amount of radiation dose reduction can be allowed [11,12,13]. Careful clinical evaluation and reconstruction parameter optimization are required before IR can be used in routine practice [10,14,15]. Task-based image quality evaluation using model observers have been actively investigated so that image quality and dose reduction can be quantified objectively in an efficient manner [16,17,18].

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