Anthony J. MacKay Student Paper Contest

The Anthony J. MacKay Student Paper Contest is organized each year by CRPA’s Student Affairs Committee. The winner receives an all-expenses paid trip to the CRPA conference to present their paper. At the conference, the winner has an opportunity to meet professionals who work in the field of radiation science—hospitals, universities, the nuclear power industry, and all levels of government. The winning paper is also published in the CRPA Bulletin.

The contest is open to full- or part-time students at a Canadian university or college whose post-secondary studies are related to radiation sciences (nuclear medicine, medical physics, radiation therapy, etc.). The topic of the papers must be a radiation-related topic.

This year’s winner was Steven Bartolac. His paper was co-authored by David Jaffray, his graduate supervisor.

Fluence Field Modulated CT
Potential for Dose and Noise Optimization in Thoracic Imaging Applications

Steven Bartolac (Department of Medical Biophysics, University of Toronto)
David Jaffray (Department of Radiation Oncology, University of Toronto)

Introduction

Recently, awareness regarding the potential risks of radiation dose due to computed tomography (CT) scans has been raised both in the general public, via reports in mainstream media, as well as among medical practitioners and physicists. A notable example of the former is the article “How Dangerous Are CT Scans,” which appeared in Time magazine (Guthrie, 2008). The latter has been evidenced in North America most significantly through the widespread campaigns Image Gently and Image Wisely, which have the general mandate of providing education on how to limit unnecessary dose to pediatric and adult patients respectively.

The heightened concern regarding the radiation risks of CT has been largely stimulated by a number of reports and papers within the last five years (Brenner and Hall 2007; Hillman and Goldsmith 2010; Smith-Bindman 2010), which have indicated both that the number of CT procedures being performed per capita is on a steady incline (estimates show a rise of roughly 10% per year in both the United States and the United Kingdom), and that the lifetime attributable risk (LAR) of cancer is non-negligible for certain procedures, especially when patients receive multiple scans. One study (Brenner and Hall 2007) estimates that on the order of 2% of future cancers in the United States will be attributable to CT imaging (Smith-Bindman 2010).

Résumé
Dans une tomodensitométrie à la fine pointe de la technologie, l’incident de la dose des rayons X sur le patient se limite essentiellement à une certaine forme (ou modèle) entre les projections (à l’aide d’un filtre en forme de noed papillon, par exemple), ne permettant qu’aux biais de la dose de se modifier (par la modu-lation d’un courant en forme de tube, par exemple). Permettre au modèle de fluence des rayons X de se modifier indépendamment pour chaque projection constitue un nouvel aspect de la tomodensitométrie modulée par un champ de fluence (FFMCT) à certaines applications d’imagerie thoracique, dont l’examen courant du thorax, le dépistage du cancer du poumon et la tomodensitométrie cardiaque. Les modèles de fluence modulée pour un ensemble de données simulées sont créés en utilisant un script d’optimisation de recuit simulé. La dose résultante et les distributions du rapport signal/bruit (SNR) sont comparées à celles qui sont optimisées à l’aide d’un filtre en forme de noed papillon et de la modu-lation d’un courant en forme de tube. Les résultats indiquent que la FFMCT a le potentiel d’accomplir des distributions du SNR variant selon les régions en bon accord avec les valeurs prescrites par l’utilisateur et avec moins de doses totales qu’avec les techniques conventionnelles de minimisation de doses.
United States may be attributable to radiation from current CT studies.

Risks due to X-ray radiation arise because CT generates high-resolution three-dimensional (3D) images from a set of X-ray radiographs (or projections), which are recorded at different angles about a patient. Generally, noise and dose share an inverse relationship in CT: decreases in exposure (and therefore dose) are accompanied by increases in noise. The goal is then to achieve a diagnostic-quality image while limiting dose as much as possible. In practice, dose to the patient is managed by applying appropriate patient- and/or task-specific tube current and energy settings on the CT unit. The energy is typically fixed based on the patient size, while the tube current can vary throughout the scan to accommodate changes in patient thickness as a function of angle or longitudinal position—referred to as angular (Papadakis et al. 2007; Giacomuzzi et al. 1996; Greess et al. 2002; Kalender et al. 1999; Kopka et al. 1995; Lehmann et al. 1997) and z-axis tube current modulation (TCM) (Imai et al. 2009; Kalra et al. 2004; Namasivayam et al. 2006; Westerman 2002) respectively. Bowtie filters (Barrett and Swindell 1981; Graham et al. 2007; Mail et al. 2009), placed in front of the beam as shown in Figure 1, have also long been used to try to achieve more uniform exposure levels at the detector, with the benefits of decreasing dose to thinner regions of the patient while also achieving more uniform noise characteristics.

More recently, innovative approaches applying more severe collimation of the beam (Chen et al. 2009; Chityala et al. 2004; Moore et al. 2006; Schafer et al. 2010; Cho et al. 2009), such that high exposure is limited to a small central region of interest, have also been proposed for large field-of-view circular CT geometries. In this case, the goal is to maintain high image quality for the target region of interest, while allowing image quality to be reduced elsewhere. These approaches have been referred to as region-of-interest imaging; however, they have not yet been adopted in practice. Dynamic collimation in the longitudinal patient direction is a recent feature that has been added to scanners to reduce radiation from the endpoints of helical scanning acquisitions, which are generally not utilized in the image reconstruction. While these techniques collectively make strides toward reduction of patient dose, the ability to manage the incident exposure is constrained to a fixed collimator or beam-
shaping filter, therefore greatly limiting the ability to compensate for the complexity of real patient anatomy in optimization of noise and dose to the patient.

Previous work (Bartolac et al. 2011; Graham 2006) has shown that allowing the fluence (number of photons per unit area) to change across the detector, both as a function of position across the detector, \( \xi \), and as a function of angular position, \( \theta \), around the patient, may have the potential for achieving user-prescribed noise characteristics as well as significant decreases in dose. This concept, referred to as fluence-field-modulated computed tomography (FFMCT), is illustrated in Figure 2. FFMCT shares parallels with intensity-modulated radiation therapy (IMRT), except “image quality plans” replace the target “dose plans” of IMRT.

Although FFMCT has shown potential for reducing dose while obtaining target image quality, the application considered previously (Bartolac et al. 2011) was artificial, with an arbitrarily identified region of interest. In this paper, we attempt to evaluate the dose and noise benefits of FFMCT in specific imaging applications of the thorax: lung screening, cardiac CT, and routine chest imaging. To date, delivery of modulated fluence fields in computed tomography applications remains a technical challenge. This paper, therefore, studies the potential contributions of FFMCT under simplifying assumptions in simulation.

Methods & Materials

FFMCT proceeds by optimizing the incident fluence field to deliver a prescribed image quality under dosimetric constraints. The fluence can ideally change as a function of detector position, \( \xi \), and angular position, \( \theta \) (see Figure 2). In the following study, we consider the case of a single slice acquisition of a chest CT scan, optimized for three different cases:

1. Cardiac CT
2. Lung Screening
3. Routine Chest Exam

Implicit in the approach for FFMCT is that an a priori model of the patient is available. This model is used to define an image quality plan, and to predict noise and dose outcomes in order to optimize the incident fluence. In many cases, a previous CT scan of the patient may be available for this purpose. Alternatively, a population-based model could be used. In this study, a simulated anthropomorphic chest phantom, containing bony anatomy, soft-tissue, and lung-equivalent regions, was used; it is depicted in Figure 3(a).

The boundaries for the high signal-to-noise ratio (SNR) values, shown in red in Figure 3(b–d), were chosen to contain a region slightly larger than the regions of interest. The regions of interest were selected to contain the imaging target in each application (e.g., region containing the heart for cardiac CT, lung for lung screening, etc.), and are illustrated graphically in the bottom right corners of Figure 3(b–d).

Optimization was performed considering a simplified parallel ray geometry, and considering only the primary fluence (no scattered radiation) in evaluations of dose and noise. These assumptions and their implications are discussed below in the Discussion section of this paper. The fluence arriving at the detector can then be modelled as a function of \( \xi \) and \( \theta \) (with units of photon counts per detector pixel), \( N(\xi,\theta) \). Optimization assumes the modulation of an arbitrary incident reference fluence field. If the reference X-ray beam is modulated by a factor of \( m(\xi,\theta) \), the modulated fluence arriving at the detector can be modelled as (Bartolac et al. 2011):

\[
N'(\xi,\theta) = m(\xi,\theta) N(\xi,\theta),
\]

where the factor \( m \) is the modulation factor; the set of modulation factors over the complete angular and linear range will likewise be referred to as the modulation profile. In addition, the commonly employed filtered back-projection reconstruction algorithm was utilized in the present study. Optimization proceeds using an iterative optimization scheme that searches for the optimal modulation profile, \( \hat{m} \), by attempting to solve the following minimization problem:

\[
\hat{m} = \arg \min_{m \in M} \left( \sum_{E} W_E(\hat{f}) (Q(\hat{f}) - Q_m(\hat{f}))^2 + \right)
\]

\[
\sum_{D} W_D(\hat{f}) (D_m(\hat{f}) - D_m(\hat{f}))^2
\]

where \( M \) is the set of all feasible modulation profiles \( m \), \( Q(\hat{f}) \) is the desired or prescribed quality metric at spatial position \( \hat{r} = (x, y, z) \), \( Q_m(\hat{f}) \) is the modulation-dependent, spatially variant quantification of the image quality within the object, \( D_m(\hat{f}) \) is the local, modulation-dependent dose, and \( W_E(\hat{f}) \) and \( W_D(\hat{f}) \) are predefined, spatially varying weighting factors that can be used to prioritize image quality and dose, respectively, at specific regions.
In the present study, the metric for image quality, \( Q(\hat{r}) \), was defined as the standard deviation of the reconstructed signal, \( n(\hat{r}) \), relative to a reference value for the attenuation coefficient of water, \( \mu_{H_2O} \):

\[
Q(\hat{r}) = \frac{\mu_{H_2O}}{n(\hat{r})}
\]

[3]

A higher Q value indicates better image quality (lower noise) and can easily be interpreted as equivalent to a high SNR with respect to water. That being said, since the noise is considered relative to a constant reference signal, it should be noted that this measure of quality is strictly a measure of the noise and is independent of the mean values in the reconstruction volume. However, since the units are the same as SNR and can be referred to refer to the quality metric Q as SNR for simplicity here. Note that other quality metrics could also have been used, such as contrast-to-noise ratio (CNR).

The first term in equation causes the solution to trend toward the prescribed SNR criteria, while the second term attempts to lower the dose as much as possible. The weights can be altered to change the priority of the SNR or dosimetric terms. A logical choice of dosimetric weights might be the organ-specific weights provided by the International Commission on Radiological Protection (ICRP). In that case, the second term would attempt to minimize the effective dose. In this study, the dosimetric weighting was set to unity for all voxels, such that each voxel has equivalent priority in the optimization scheme with respect to dose minimization. A higher weighting (by a factor of 10) was applied to the prescribed high-quality region of interest for the SNR term in order to prioritize image quality in these regions. Computation of equation at each iteration required a prediction of the standard deviation as a function of voxel position. For this purpose we used a model for the variance of the noise, derived by Kak and Slaney (1988) for the case of parallel-ray, filtered back-projection reconstruction methods:

\[
\text{var} (f(\hat{r})) = \left( \frac{\pi T}{M_{proj}} \right)^2 \sum_{\theta \in \mathbb{R}} \frac{1}{N(\theta, \xi)} h^2(x \cos \theta + y \sin \theta - \xi)
\]

[4]

where \( M_{proj} \) is the number of projections, \( t \) is the width of the detector pixels, and \( h \) is the convolution kernel in the filtered back-projection operation. Simulations verified that this expression was accurate to within 5% for the prediction of the variance (or standard deviation squared). Optimization of equation was carried out using a simulated annealing optimization method, described in detail in a previous publication (Bartolac et al. 2011). Dose calculations were modelled from the collision kerma, \( K_c(\hat{r}) \), which accurately represents the dose at energy levels used in computed tomography:

\[
D(\hat{r}) = K_c(\hat{r}) = \psi(\hat{r}) \frac{\mu_{en}(\hat{r})}{\rho(\hat{r})}
\]

[5]

where \( \psi(\hat{r}) \) is the primary energy fluence, assuming each photon has an energy of 60 keV, \( \mu_{en}(\hat{r}) \) is the mass-energy absorption coefficient, and \( \rho(\hat{r}) \) is the material density. In order to reduce the computation time required for the optimization, low-resolution images were considered of the input model and for the target image quality plans (64×64 bins, 0.54×0.54 cm voxel size). For comparison of the results, the optimization was repeated by constraining the modulation profile for each projection to the shape of a bowtie filter. This situation can be viewed as equivalent to applying tube current modulation with a bowtie filter in place, except the degree of bias applied in tube current modulation is optimized using the methods defined above. In this way, the bowtie plus tube current modulation can be viewed as FFMCT applied using a constrained modulator. Dose outcomes were compared considering integral dose (in joules) as well as the relative distribution of dose achieved in each situation.

Finally, sample reconstructions of images that included Poisson noise based on the prescribed modulation profiles are shown in order to visualize the impact of fluence modulation in practice.

**Results**

Figure 4 shows the resulting modulation profiles for each of the three thorax CT imaging cases identified. The larger number of degrees of freedom in FFMCT resulted in more complex fluence patterns for each of the cases when compared with the patterns produced using the bowtie filter. However, it can be observed that the modulation profiles constrained to the bowtie filter show peaks in tube current at similar projection intervals to those of the FFMCT cases.
the prioritized high-SNR regions was also observed for the FFMCT cases, compared with results for use of the bowtie filter with tube current modulation.

Figure 6 shows dose comparisons for the three scenarios under the differing constraints. Integral dose decreases (in joules) were found to be 23% for the heart, 5% for the lung, and 4% for the routine diagnostic cases when compared with use of the bowtie filters. Figure 6 also shows the subtraction images of the dose distributions, indicating that both relative increases and decreases in dose occurred for the FFMCT cases, compared with use of the bowtie filter with tube current modulation (warm colours indicate increases).

High-resolution image reconstructions with added simulated noise predicted by the FFMCT modulation profiles for the routine diagnostic and lung screening exams are shown in Figure 7, for comparison with the predicted SNR outcomes. Figure 7(b) shows that greater noise and corresponding streak artifacts are evident in the lung screening case but do not impede visualization of the lesion within the region of interest within the lungs, where image quality remains consistent with that of the routine diagnostic scan. An added soft-tissue lesion with a deviation of approximately 4% in signal value is also seen in Figure 7(c), shown at a different contrast level and corresponding to the boxed region in Figure 7(b).

Discussion

This study was carried out to evaluate whether potential noise and dose benefits exist when applying FFMCT to specific imaging tasks of the thoracic region. The results indicated that FFMCT could potentially meet user-prescribed image quality criteria to a higher degree over what could be achieved by conventional modulator designs in practice today. Benefits were particularly pronounced for the case of cardiac CT, where FFMCT achieved approximately 23% integral dose reduction and higher, more uniform SNR values within the region of interest. While FFMCT application to the routine chest...
Conclusions

The results of this study support the hypothesis that FFMCT can potentially be employed to decrease dose to the patient while achieving image quality to a level prescribed by the user. Specifically, three specific thoracic imaging tasks were considered that showed that FFMCT could potentially reduce dose and significantly improve image quality in the related regions of interest when compared with conventional dose reduction methods.

References


