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Experimental evaluation of dual Multiple Aperture Devices for Fluence Field Modulated X-Ray Computed Tomography

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Abstract

Acquisition of CT images with comparable diagnostic power can potentially be achieved with lower radiation exposure than the current standard of care through the adoption of hardware-based fluence-field modulation (e.g. dynamic bowtie filters). While modern CT scanners employ elements such as static bowtie filters and tube-current modulation, such solutions are limited in the fluence patterns that they can achieve, and thus are limited in their ability to adapt to broad classes of patient morphology. Fluence-field modulation also enables new applications such as region-of-interest imaging, task specific imaging, reducing measurement noise or improving image quality. The work presented in this paper leverages a novel fluence modulation strategy that uses “Multiple Aperture Devices” (MADs) which are, in essence, binary filters, blocking or passing x-rays on a fine scale. Utilizing two MAD devices in series provides the capability of generating a large number of fluence patterns via small relative motions between the MAD filters. We present the first experimental evaluation of fluence-field modulation using a dual-MAD system, and demonstrate the efficacy of this technique with a characterization of achievable fluence patterns and an investigation of experimental projection data.

INTRODUCTION

Modern CT scanners have the ability to control x-ray technique settings like tube current and tube voltage. Most scanners can perform tube current modulation (TCM) as a function of rotation angle, and also employ bowtie filters for spatial shaping of the x-ray beam. Fluence-field modulated x-ray CT (FFM-CT) extends acquisition flexibility for more general spatial and temporal modulation of x-ray fluence with the ability to specify fluence as a function of both rotation angle and position on the detector. There exists significant potential for dose reduction using hardware-based fluence field modulation [1,2] with the ability to deliver x-ray where they are needed to achieve good image quality without overexposing regions that require lower exposures. Furthermore, additional flexibility in exposure allocation enables control of measurement noise (e.g.: driving more fluence to photon starved regions) and better utilization of dynamic range of detectors. Customization of fluence fields to the patient and imaging task opens new avenues of exploration such as region-of-interest imaging [3], task-driven imaging [4], and adaptation to patient position.

Recent work by CT researchers have explored a number of hardware based strategies for fluence field modulation, including utilizing digital beam attenuators [5,6], dynamic bowties that mimic the object being scanned [7] and fluid-filled dynamic bowtie filters [8,9]. Inclusion of these novel hardware-based methods in modern clinical CT scanners requires addressing a number of mechanical challenges such as the small amount of space available in front of the x-ray tube, the requirements of rapid actuation of the fluence-field pattern as a function of rotation angle (with rotation speeds up to 5 Hz), the ability to withstand G-forces associated with high rotation speeds, and weight constraints.

A new class of novel fluence field modulation filters, designated as Multiple Aperture Devices (MAD), that work by either completely blocking or passing x-rays on a fine scale, was recently introduced [10]. An illustration of the how these filters operator on a fine scale is shown in Figure 1. Each MAD device is comprised of thin bars of a highly attenuating material. A MAD device is modulated by varying the width of each bar and its local offset. Fluence from the source is blocked if either MAD device block the beam. Shifting MAD1 with respect to MAD0 results in creation of new fluence patterns. A large range of fluence patterns can be generated by shifting the filters slightly with respect to each other. In optical regimes, this phenomenon is termed as the Moiré effect. The simulation and design of dual-MAD systems was recently investigated [12]. An optimization framework that uses an off-the-shelf optimization framework (CMA-ES [13]) was developed. This design framework enables exploration of MAD configurations that generating fluence patterns that best fit a family of desired target fluence profiles.

In this work, we investigate a prototype FFM system using dual MADs. The MAD filters are constructed from thin bars of highly attenuating material (tungsten), of varying width arranged at a high frequency. These novel binary filters are potentially spectrally neutral due to the on/off characteristic of the device. The following section describe the dual-MAD design process, the fabrication, and evaluation of the MAD-based FFM-CT system using a test-bench system.

METHODS

1. Dual MAD design and application geometry

Recently, an optimization framework for the design of dual MADs was proposed [12]. Under this framework, a mathematical parameterization of the dual MADs was proposed. Each MAD was constrained to be a periodic collection of apertures separated by blocking bars. The width of the aperture along the central MAD plane is variable – passing more or less x-rays depending on this width. Two MADs, MAD0 and MAD1 are placed in series (See Figure 2). The fluence patterns which this dual MAD system can achieve are given by the width of the bar of MAD0, $b_0(x)$, the width of the bar in MAD1, $b_1(x)$, and the local offset function of MAD1 bar with respect to MAD0, $\delta(x)$. Additionally, there exists an actuation control parameter, (θ) , which specifies the relative displacement of MAD1 with respect to MAD0. Lastly, the interval between apertures is referred to as the MAD pitch. We use a variable MAD pitch to match the first null frequency associated with X-ray focal blur. This minimizes the appearance of the high frequency bar patterns of the MAD on the detector plane leaving the desired lower spatial frequency beam modulations. The physical

variables defining a dual MAD system $\{b_0(x), b_1(x), \delta(x), \text{ or } (\theta)\}$ were further parameterized for lower dimensionality using a set of Fourier bases. Optimal designs were chosen based on a minimum mean square error metric between target fluence patterns and a model of the achievable fluence patterns (a function of the physical parameters). The design framework focuses on normalized target fluence patterns since TCM allows scaling of the intensity of the achievable fluence shapes to meet the exact target fluence patterns.

The application geometry and test-bench used for evaluation is depicted in Figure 3. The MADs are designed on a central MAD plane, 341 mm from the X-ray source. The MAD devices were mounted on linear motion stages (Velmex, Bloom-field, NY) and positioned in front of the X-ray source. The ovate phantom used for investigations is 200 mm on the short axis and 300 mm on the long axis. The phantom mimics the size of the human torso region and is the same form as a commercially available phantom (QRM, Möhrendorf, Germany), but is uniform acrylic.

While one might choose a number of different fluence field goals including region-of-interest imaging, designs to limit dynamic range, minimize image noise, or modulations driven by the specific imaging task [4], the initial investigations in this paper focus simply on flattening the fluence of the ellipse phantom, beyond the phantom and at the detector plane. Toward that end, a poly-energetic model was used to compute the target fluence pattern. Specifically, we chose a tube voltage of 100 KV, with 2 mm Al and 0.2 mm Cu. The spectral profile of the x-ray tube was modeled using Spektr [11], a computational tool for x-ray spectral analysis. Photon cross-sections for the acrylic phantom were based on NIST XCOM. The detector panel is a Varian 4343CB, which has a 0.6 mm thick CsI. The detection efficiency of the panel included an energy-weighted signal model.

2. Design output and MAD fabrication

The design framework estimates an optimal using Covariance Matrix Adaptation-Evolutionary Strategy (CMA-ES [13]), a non-linear optimization library that does not require the computation of the gradient or the Hessian. The framework, written in C++, and parallelized using the OpenMP library was utilized in generating MAD designs for manufacture. The design outputs for the field flattening task and the acrylic ovate phantom are depicted in Figure 4. Note the differences in the two MAD designs. MAD0 is unimodal, with thinner bars at the center permitting more x-ray fluence, and thicker bars at the edge. MAD1 is bimodal with a two peak bar widths on either side of the central ray. The actuation control required for the ovate acrylic phantom is also shown. Note that only 0.2 mm of relative motion is required to achieve the desired target patterns.

These designs were modified slightly to accommodate manufacturing constraints (specifically, we were limited by a minimum bar thickness of 100 μm). The main change from the design in Figure 4, appears at the edges of MAD1 where the designed bar width is less than 100 μm . The multiple aperture devices were fabricated at Philips Smit-Rontgen facility (Best, Netherlands) and can be seen in Figure 5. The fabrication process utilized a metal additive manufacturing technique called Powder Bed Laser Melting. Each MAD was printed using tungsten powder, and due to the melting process, nearly full density of metal is achieved. With a MAD thickness of 2 mm and presuming an effective beam energy of 60

keV, we expect that the tungsten bars pass only 0.000065% of the incident x-rays, yielding a nearly binary filter.

3. Evaluation experiments

We conducted experiments to a) measure the fluence-field maps achievable utilizing the dual MADs; b) studied the motion profile of MAD1 and tube current requirements; c) measured the bare-beam fluence utilizing MAD and TCM; and d) investigated the ability of dual MADs to flatten the fluence field on detector plane for the ovate phantom. To determine actuation control for the phantom, a best fit between the required fluence and achievable fluence (as measured) was applied. This best-fit actuation was compared to the predicted/design control actuation.

RESULTS

The photograph of fabricated dual MADs is shown in Figure 5. The minimum bar width of 150 μm and minimum slot width of 100 μm . The manufactured dimension of the MAD was 170x27x2 mm, weighing 130g. The MAD bars are angled so that all are aligned to a diverging beam focused back to the X-ray source. At the edge, this angulation is approximately 12° corresponding to one-half the fan angle. Four sample x-ray projection images are shown in Figure 6. Each image shows the detected signal at a different displacement of MAD1. Specifically, we show relative displacements of 320, 472, 630, and 775 μm . Note the dramatic change in the spatial profile of the x-ray beam that is achieved with relatively little motion. While we have leveraged focal spot blur in the design of the dual MAD system, we note that some residual high-frequency modulation associated with the bars is apparent in these projection images.

A complete fluence map, showing all possible spatial modulations was generated by shifting MAD1 over one complete interval from 0 to 0.8 mm. Both the predicted fluence map (simulated as part of the design process) and the experimental map (showing fluence for one row of the detector) are shown in Figure 7. The simulated fluence map depicts the ability of MAD devices to modulate the fluence beam from very narrow (0.6 mm) to flat beam (0.1 mm). The two maps have relatively good correspondence; however, the residual high frequency modulations are apparent and there is a slight scaling along the x-axis. Note that the fluence is increased at the edges of the detector panel. These locations are outside the ellipse phantom and were ignored during the optimization process.

Figure 8 depicts both the MAD1 displacement and TCM required to achieve the objective of flattening the fluence field, as a function of rotation angle of the x-ray system. Both the predicted/simulated controls and the best fit controls (based on the above characterization) are shown. The experimental curves match well with the predicted actual but show slight deviations, potentially due to the residual high frequency modulations and scaling discussed above. The experimental measured TCM is also subject to changes due to tube warm-up.

Figure 9 shows the bare-beam fluence generated by the MAD devices in conjunction with TCM, for flattening the ovate phantom. The fluence on the detector panel utilizing both MAD and TCM through the ovate phantom is shown in Figure 10. We see successful

flattening of the detector in both simulation and experimental results. There are some differences – notably at the edges of the phantom. This is, in part, due to the reduced dimensionality of the optimization but also due to manufacturing limitations that limit bar-width and slot-size.

CONCLUSION

This paper has presented the first experimental evaluation of a novel fluence field modulator based on MAD filters. A simple fluence field objective and object was chosen and a dual MAD modulator was designed based on a nonlinear optimization framework. The MAD devices were manufactured using a laser sintering process. The manufactured prototype is compact, has relatively low weight, and has small actuation distance requirements that may facilitate integration of such devices within a modern CT gantry. The experimental performance of the filters matched well with simulated predictions of performance. In phantom results, the fluence field was successfully modulated spatially and temporally using the MADs to achieve largely uniform detector signal over the projection of the object. These initial results suggest that MAD-based fluence-field modulation is practical, providing a novel approach for increased flexibility in CT acquisitions. Ongoing studies are looking at the imaging chain for reconstructing MAD-based, fluence-field-modulated data, and the image quality and radiation exposure trade-offs in dual-MAD acquisitions – with particular attention to opportunities for dose reduction in x-ray CT.

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Figure 1.

A dual-MAD fluence-field modulator. Fine scale binary filters permit a range of fluence fields by translating MAD1 with respect to MAD0 over small displacements.

Figure 2.
MAD parameterization for design optimization

Figure 3.

Illustration of the experimental setup. An SDD of 1040 mm, SAD of 803 mm was chosen to mimic a CT scanner. The MADs are placed 341 mm from the source, with inter-MAD separation of 10 mm. The ellipse phantom has a length of 300 mm and width of 200 mm.

Figure 4.

The parameters of the dual-MAD design for the acrylic phantom and flat-detector signal objective. Both physical parameters and the control parameter to achieve the flat-field are illustrated.

Figure 5.

Optical photograph of manufactured MADs. The tungsten bars are focused back to the x-ray source to accommodate the divergent cone beam. This image was taken with backlight illumination with the camera at the focus of the MAD bars.

Figure 6.
Projection images obtained with four different MAD1 shifts () showing ability to modulate fluence.

Figure 7.
Fluence map generated by shifting MAD1 over a full interval (0 to 0.8 mm).

Figure 8.

MAD1 displacement and tube current modulation as a function of rotation angle. The blue curve shows data from simulation using MAD design. The red curve shows experimental data.

Figure 9.

Bare-beam detector signal utilizing both MADs and TCM. The data is normalized such that mean across the boundaries of ovate phantom is unity.

Figure 10.

Detector signal with MADs and TCM with ovate phantom. The data is normalized such that mean across the boundaries of ovate phantom is unity.