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Scout-view Assisted Interior Micro-CT

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Abstract

Micro computed tomography (micro-CT) is a widely-used imaging technique. A challenge of micro-CT is to quantitatively reconstruct a sample larger than the field-of-view (FOV) of the detector. This scenario is characterized by truncated projections and associated image artifacts. However, for such truncated scans, a low resolution scout scan with an increased FOV is frequently acquired so as to position the sample properly. This study shows that the otherwise discarded scout scans can provide sufficient additional information to uniquely and stably reconstruct the interior region of interest. Two interior reconstruction methods are designed to utilize the multi-resolution data without a significant computational overhead. While most previous studies used numerically truncated global projections as interior data, this study uses truly hybrid scans where global and interior scans were carried out at different resolutions. Additionally, owing to the lack of standard interior micro-CT phantoms, we designed and fabricated novel interior micro-CT phantoms for this study to provide means of validation for our algorithms. Finally, two characteristic samples from separate studies were scanned to show the effect of our reconstructions. The presented methods show significant improvements over existing reconstruction algorithms.

Keywords

computed tomography (CT); interior tomography; scout-view; multi-resolution acquisition; truncation artifact; compressed sensing

1. Introduction

A major limitation of computed tomography (CT) has been that the imaging field-of-view (FOV) needs to cover the entire sample. If this is not the case, i.e. the sample is larger than the FOV, projections are truncated in some or all of the views. Truncated projections have no unique reconstruction value (Natterer 2001). Typically, the effect of truncated projections is seen in reconstructed images in the form of cupping artifacts at the edges (resulting in a loss of contrast in features), and a difference in CT numbers (a DC bias) when compared

with global reconstructions containing the whole sample in the FOV (Costin et al. 2011, Herman & Lewitt 1981, Yu & Wang 2009). High-resolution micro-CT scanners employ projection x-ray imaging using laboratory sources to achieve resolution on the order of $1\ \mu\text{m}$ (Feser et al. 2008, Ritman 2004). In such scanners, the FOV varies between 0.5 mm and 1 cm, with higher resolution at smaller FOV-s (Stock 2008). Hence truncated projections are a very common problem, particularly as interest in higher resolution imaging increases, and the option of trimming the sample to an appropriate size matching the FOV is not desirable.

Over the years, multiple techniques have been proposed to circumvent the interior tomography problem; some of which are listed here:

- i. In the field, the most commonly used approach is based on sinogram extension techniques (Kolditz et al. 2011, Lewitt & Bates 1978, Van Gompel 2009). However the extension techniques are necessarily approximation methods, and do not achieve exact reconstruction.
- ii. A second group of techniques employ a combination of back projection of the first derivative and the 2D Hilbert transform (Defrise et al. 2006, Noo et al. 2004); however they deal with a certain class of truncated projections only, and are unstable in case of completely interior truncation, where the region of interest (ROI) is fully inside the object (Costin et al. 2011).
- iii. Lambda tomography accurately locates discontinuities inside the ROI (Faridani et al. 1992, Yu & Wang 2006), but does not provide CT number information.
- iv. A compressed sensing (CS) based technique (Yu & Wang 2009) has been shown to achieve accurate interior reconstruction in many imaging modalities including cardiac CT (Yu et al. 2011), MRI (Wang et al. 2011), electron microscopy (Goris et al. 2011). However the iterative procedure is highly time consuming and is not yet commercially viable (Pan et al. 2009).

This paper introduces two novel interior reconstruction methods, namely ‘scout-interpolation’ and ‘scout-reconstruction’, that use only a handful of scout views as additional information. The new methods are compared with two previously reported methods – ‘truncated-FBP’, which is a sinogram extension technique (Hoppe et al. 2008), and ‘sequence subsets SART-TV (SS-SART-TV)’, a compressed sensing aided reconstruction algorithm (Yu & Wang 2009, Ogawa & Urabe 1999).

Scout views are global projections that encompass the entire object. Before any interior micro-CT scan, some scout projections are typically acquired as they help to place the sample within the FOV, and to align the sample along the axis of rotation. However the scout views are usually discarded. In this study, we show how the scout views may be used to mitigate interior reconstruction artifacts. Also a “scout tomography” consisting of just a few global views at low resolution may easily be acquired just for the purpose of accurate interior reconstruction.

Multi-resolution acquisition (or “zoom-in” tomography) uses a low resolution scan to fill up the incomplete information in high-resolution truncated projections (Maaß et al. 2011, Nalcioglu et al. 1979, Pak-Kong Lun & Hsung 1997, Sahiner & Yagle 1995, Tisson et al. 2004). Most previous multi-resolution approaches placed severe restrictions on the relative geometry of the two scans, making them difficult to undertake experimentally (Costin et al. 2011, Kyrieleis et al. 2010). No such restrictions are required in this study. In (Maaß et al. 2011), two multi-resolution methods were proposed and compared to the gold-standard (the “data-completion” method) – all three techniques had no restrictions on the relative geometries. Yet, like most multi-resolution techniques thus far, their methods required the low-resolution scan to be adequately sampled over the angular range. In contrast, we only

require a minimal set of global or scout views, with no significant time impact. Of our two proposed methods, scout-interpolation is an extension of multi-resolution acquisition techniques, while scout-reconstruction enhances the data-completion method (Maaß et al. 2011) by incorporating compressed sensing aided reconstruction in the low-resolution reconstruction step.

In (Bharkhada 2010, Yu et al. 2009), reconstruction schemes were developed which used only two scout views to eliminate interior reconstruction artifacts. The reconstruction methods described in those two studies were purely iterative techniques. However, CT manufacturers tend to prefer the traditional filtered back projection (FBP) algorithm over iterative reconstruction algorithms (Pan et al. 2009). Two important reasons for this preference are that, (1) users are familiar with FBP in terms of reconstruction parameters, achievable image quality etc., and (2) manufacturers have already developed optimized image reconstruction chains using FBP, and the migration to purely iterative reconstruction requires significant spending and engineering effort. The methods in this paper employ FBP for the final reconstruction, and thus, new user training is not required. Though one of the two algorithms in our paper employs an iterative reconstruction step, the additional computational burden is very low as shown in Sec. 4. Thus, the proposed algorithms may be easily integrated into existing reconstruction chains.

In most previous studies on interior reconstruction, interior scans were simulated by numerically truncating real global projections (Sahiner & Yagle 1995, Taguchi et al. 2011, Yu & Wang 2009). Such an approach is essential to verify new algorithms by comparison to the ground truth. The presented study goes one step further and investigates scans where the truncated projections and scout views were acquired in separate scans with two different magnification images using two different size detectors. For such multi-resolution scans, various factors come into play (e.g. registration, detector differences), that were handled by proposed interior reconstruction methods.

Furthermore, novel interior micro-CT phantoms were fabricated using conventional lithography techniques, and “off-the-shelf” items. Firstly, a phantom for interior scans should be larger than the FOV of the detector. Then it should have known geometric structures embedded within the interior ROI, so as to allow proper system characterization. In clinical CT where resolution is in the millimeter range, such geometrically well-defined structures (e.g. wire, spherical, and square phantoms) are commercially available (Kalender 2011). In high-resolution micro-CT, the most commonly used phantoms are thin test patterns fabricated by semiconductor fabrication techniques, but they allow system characterization in the projection domain only (Sen Sharma et al. 2011). 3D micro-CT phantoms allowing quantification in reconstructed slices (Mizutani et al. 2010) have been difficult to fabricate, or are not yet readily available (Sen Sharma et al. 2013). Most importantly, previously reported micro-CT phantoms were not suitable for characterizing interior reconstruction, and thus, new phantoms were fabricated for this study.

The remainder of the paper is organized as follows. The micro-CT phantoms, micro-CT samples, scan protocols, and interior reconstruction algorithms are detailed in Sec. 2. Section 3 discusses the results obtained on micro-CT phantoms and samples. Finally, Sec. 4 concludes the paper with a discussion and summary.

2. Materials and Methods

2.1. Micro-CT scanner

All scans were carried out on a MicroXCT-400 scanner from Xradia Inc. (Pleasanton, CA). This scanner employs a commercially available microfocus x-ray source to achieve

projection imaging. The x-rays are absorbed by a scintillator and converted to visible light – a microscope objective then focuses this light onto a 2048×2048 CCD (Feser et al. 2008). Depending on the magnification lens used, the effective detector pixel size may be varied between $27 \mu\text{m}$ and $0.3 \mu\text{m}$. Furthermore, the geometric magnification of the system may be modified by moving the source and detector stages according to the needs of the scanned specimen. The sample can be translated in the x - y - z directions on a high precision stage. The translation stage is mounted atop the rotation stage, and this allows the selection of any axis of rotation within a sample. The scan protocols used in this study are detailed in Sec. 2.3.

2.2. Micro-CT phantoms and samples

Two interior micro-CT phantoms, and two typical micro-CT samples were scanned as part of this study.

2.2.1. Interior micro-CT phantom—I—Wafers of micro-gas chromatography devices consisting of an array of micro-pillars were first fabricated (Alfeeli et al. 2008). Next, $\sim 300 \mu\text{m}$ wide strips were diced off to create structures that fit within FOV of a high resolution micro-CT (Sen Sharma et al. 2013). These structures are marked by white arrows in Fig. 1A. To create an interior phantom, the micro-pillar strips were bundled with other sub-mm structures – specifically, PMMA micro-capillary tubes (Paradigm Optics, Inc., Vancouver, WA) of varying diameter and material (two such tubes are marked by black arrows with white borders in Fig. 1A). White duct tape and Scotch tape (3M Inc., Maplewood, MI) were used as packing material, and also provided additional attenuating material. The bundle of Fig. 1A has a diameter of $\sim 6.7 \text{ mm}$ that is considerably larger than the $\sim 2.8 \text{ mm}$ FOV of $1.4 \mu\text{m}$ pixel size detector used to acquire interior projections. This bundle is referred to as interior micro-CT phantom I. The phantom had a circular cross-section, and the objects of interest (i.e. the micropillar strips) were placed near the center of the phantom.

2.2.2. Interior micro-CT phantom II—Using sub-mm structures described above in Sec. 2.2.1, duct tape, and Scotch tape, another bundle was created as shown in Fig. 1B. It had a non-circular cross-section, and a region of interest quite far from the geometric center of the phantom (marked by dotted white square in Fig. 1B). This bundle is referred to as interior micro-CT phantom II.

2.2.3. Rock sample—The characterization of carbonate rock pore structure is of importance in the sciences of natural resource extraction and carbon sequestration. From the pore structure, rock properties such as porosity, pore connectivity, permeability and capillary pressure can be derived and used in subsequent analysis. Results of such methods depend upon accurate 3D imaging and segmentation of rock samples, frequently acquired through interior tomography. Fig. 1C shows a reconstructed slice from a global scan of an exemplary carbonate rock sample.

2.2.4. Mouse lung—In recent morphometric studies of murine lungs, high-resolution micro-CT scans were carried out on perfusion fixed mouse lungs (Vasilescu et al. 2012). A complex imaging protocol was developed (Vasilescu et al. 2012) in which the entire lung was first imaged with the $27 \mu\text{m}/\text{px}$ detector of the Xradia MicroXCT-400 scanner. A reconstructed slice is shown in Fig. 1D. At this magnification the entire lung fit in the FOV and enabled the precise selection of coordinates at which high resolution scans could be performed. The high-resolution interior scan was performed using the $1.4 \mu\text{m}/\text{px}$ detector, and enabled the 3D reconstruction and quantitative study of the acinar structures, the basic ventilatory units in the lung that consist of a complex grape like structure (Vasilescu et al. 2012). Such a multi-resolution study design is essential for imaging fragile biological

sample where the morphometry of internal structures can be altered by physical dissection as traditionally done for histological studies.

2.3. Scan protocols

For all samples listed in Sec. 2.2, global scans were first carried out. Reconstructed slices for the four samples are shown in Fig. 1. The detector pixel size used in each such scan is marked at the top-right corner of all images in Fig. 1 ($27\ \mu\text{m}$ pixel size detector for all samples, except rock sample, where $3.4\ \mu\text{m}$ pixel size detector was used). 1500–1800 projections were acquired for each global scan so as to allow sufficient projection sampling and low reconstruction noise – the exact number of projections used are listed in Tab. 1. Reconstructions of global scans were used as a ground truth for comparing interior reconstruction results.

Next, scans targeting an interior ROI were acquired. The interior scans were acquired using $1.4\ \mu\text{m}$ pixel size detector each time, and the ROI is marked by white border in subfigures 1B–D.

2.3.1. Truncated sonogram—The global sinogram of the central slice of interior phantom I is shown in Fig. 2A. Global projections were truncated to simulate corresponding interior data, as shown in Fig. 2B. The truncated data are perfectly co-registered with global data and thus allow straightforward comparison of various interior reconstruction algorithms, and omit other sources of reconstruction differences. The truncation ratio (higher ratio signifying more truncation) was calculated as below:

$$\text{Truncation ratio} = 1 - \frac{\text{Length of truncated projection}}{\text{Length of global projection}} \quad (1)$$

For the other samples, interior scans provided already truncated views and sinograms.

2.3.2. Scout views—While the global scans were acquired at large number of projection angles, the entire global scan was not used as additional information for improved interior reconstruction. From the large set of global projections, two to eight views were selected as scout views and used as additional information. The scout views were selected at equal angular sampling as shown for the six scout view case in Fig. 2C. The small number of additional scout views do not represent an additional scan burden and yet significantly reduce interior reconstruction artifacts, as we will show subsequently.

There are two possible configurations for global scout views w.r.t. the interior scan, and these are depicted in Fig. 3. First, the global scout views may be acquired at the same scan geometry (i.e. same axis of rotation, source distance, detector distance etc.) as the interior scan. Such a scan is depicted in subfigure 3A, and occurs in real scans when the only change between the scans is the change of the detector. Second, the interior scan and global views may be acquired at completely different geometries. As depicted in subfigure 3B, the two source positions (S_H and S_L) and detector positions are different; also the axes of rotation are different. In our samples, the scan and subsequent truncated projections for sample A in Fig. 1 obey the former configuration, while the data acquisition for samples B, C, D in Fig. 1 obey the latter configuration.

2.4. Interior reconstruction algorithms

The Xradia MicroXCT-400 scanner used in this study employs scanning in cone-beam geometry. In the presented study, only the central slice of the cone-beam (which can be

described by fan-beam geometry) was considered, so as to allow faster execution by limiting the problem to 2D (De Man et al. 2005). The main motivation of this study was to introduce two new interior reconstruction algorithms and compare them with existing techniques; the extension to cone-beam was left as a future task. The trend in results observed by fan-beam reconstruction on the central slice is expected to be same for all slices when reconstructed by cone-beam reconstruction; it is well known that practical Feldkamp-type cone-beam reconstruction methods are based on modified fan-beam reconstruction formulas (Wang et al. 1993).

Four algorithms were used to reconstruct the truncated projections. The first two methods – truncated-FBP (Sec. 2.4.1) and sequence subsets SART-TV (Sec. 2.4.2) are previously reported methods that use only the truncated sinogram. Scout-interpolation (Sec. 2.4.3) and scout-reconstruction (Sec. 2.4.4) are two new methods introduced in this paper, and use truncated sinograms as well as scout views. Further details of the algorithms are explained below.

2.4.1. Truncated-FBP—If FBP is directly applied on a truncated projection (where unknown projection values are replaced by zeros), the reconstructed image suffers from severe cupping artifacts, and a loss of contrast (Costin et al. 2011, Van Gompel 2009). To reduce this problem, a Gaussian extrapolation technique (Hoppe et al. 2008) was employed, where the border value of the truncated sinogram was rolled off to zero by a Gaussian function. Also, as the knowledge of actual object boundary is not provided to this algorithm, the extrapolation range is selected ad hoc. The resulting sinogram is shown in Fig. 2D. FBP was employed on the Gaussian extrapolated sinogram to yield the reconstructed image. This process of FBP after Gaussian extrapolation of the sinogram is henceforth referred to as ‘truncated-FBP’ in the paper.

2.4.2. Sequence subsets SART-TV (SS-SART-TV)—In (Yu & Wang 2009), compressed sensing based SART-TV reconstruction was shown to provide higher accuracy for interior reconstruction as compared to FBP. Each iteration of SART-TV consists of one step of SART (simultaneous algebraic reconstruction technique), and one step of total variation (TV) minimization. In this study, while the TV minimization step was kept the same, the SART step was replaced by sequence subsets SART (SS-SART) (Ogawa & Urabe 1999, Urabe & Ogawa 1998). SS-SART allowed the image update to progress in a very stable fashion, and also achieved better image quality at a lower number of iterations (Kong & Pan 2011).

The starting point for SS-SART-TV reconstruction is the truncated sinogram without any extrapolation (as in Fig. 2B), and the initial image is composed of zeros. Only three parameters are required to be set in this process: relaxation parameter λ of SART at 0.8, α parameter for TV minimization at 0.2, and number of TV iterations at 5. In our tests, this combination of parameters yielded good results for all four datasets.

2.4.3. Scout-interpolation—For the scan configuration of Fig. 3A, global scout views and interior scan are acquired at identical source-detector positions and at the same axis of rotation (only the detector is changed). Reconstruction by ‘scout-interpolation’ is carried out as explained below.

- i. Scout views $P_L(m\tau_L, \theta_i)$ $\{m = -M, \dots, M; i = 1, 2, \dots, N_{\text{Scouts}}\}$ are originally acquired at lower magnification detector pixel width τ_L . The scout views are up-sampled by cubic spline interpolation to the detector pixel width τ_h ($\tau_h < \tau_L$) of the high-resolution interior scan. This yields

$$P'_{LH}(n\tau_h, \theta_i) \{n = -N, \dots, N; i = 1, 2, \dots, N_{\text{Scouts}}\}.$$

- ii. Next, since the scout views are acquired at only a few projection angles i.e. $N_{\text{Scouts}} \ll N_{\text{Proj}}$, a cubic spline interpolation and extrapolation step (MATLAB, The MathWorks, Inc., Natick, MA) estimates the projections at all angles of the interior projections. This yields $P_{LH}(n\tau_H, \phi_j) \{n = -N, \dots, N; j = 1, 2, \dots, N_{\text{Proj}}\}$.
- iii. The portion of the sinogram corresponding to the ROI is replaced by the high-resolution interior scan $P_H(n\tau_H, \phi_j) \{n = -P, \dots, P; j = 1, 2, \dots, N_{\text{Proj}}\}$, where $P < N$. This step yields a sinogram like that in Fig. 2E. To blend the sinograms without abrupt change in intensity, a sinogram equalization step is carried out as described in (Chityala et al. 2005).
- iv. The resulting sinogram is reconstructed using FBP.

2.4.4. Scout-reconstruction—When the global scout views and interior scan do not share similar geometry (as in Fig. 3B), the scout-interpolation method cannot be applied. We developed a novel ‘scout-reconstruction’ method as explained below. Fig. 4 also provides a schematic of this algorithm (with the steps below being marked in the figure).

- i. High-resolution interior scan P_H is acquired at source position S_H and with detector pixel width τ_H .
- ii. Global scout views P_L are acquired from source position S_L , using a lower magnification (with detector pixel width τ_L , where $\tau_H < \tau_L$).
- iii. Using only sinogram P_L composed of scout views, SS-SART-TV is carried out (all parameters same as in Sec. 2.4.2, except that 20 TV iterations are performed in each TV minimization step).
- iv. The resultant image I_S is forward projected from source position S_H in the high-resolution geometry (still at detector pixel width τ_L of low-resolution detector, but at all projection angles of the interior scan).
- v. Each column of the forward projected sinogram P_{LH} is up-sampled to the high-resolution pixel width τ_H . The forward-projected and up-sampled sinogram contains some irregularities (e.g. striped patterns marked by white arrows in figure), but this does not affect final reconstruction adversely. Next, the region corresponding to the ROI is replaced by real interior projection data P_H . Sinogram equalization according to (Chityala et al. 2005) is performed prior to blending of sinograms so as to avoid abrupt change in intensity.
- vi. Finally, the merged sinogram is reconstructed using FBP.

Step (iv) requires an accurate registration between the global and interior scans. This is easily achieved as the Xradia MicroXCT-400 records the exact location of the iso-center in terms of world co-ordinates for both the scans.

3. Results

3.1. Results: Interior micro-CT phantom I

3.1.1. Reduction of interior reconstruction artifacts—Global projections were numerically truncated up to truncation ratios of 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8, and then reconstructed using the four methods listed in Sec. 2.4. A line profile was drawn across the reconstructed slice as shown in Fig. 5C. The various line profiles at different truncation ratios and for each reconstruction algorithm are compared in Fig. 5. Subfigure A compares the line profiles for truncated-FBP with global FBP (the ground truth). It is easily seen that as the truncation increases, the DC bias and cupping around the edges also increases. In subfigure B comparing SS-SART-TV, it is observed that DC bias and cupping artifacts

exist, but are much lower than truncated-FBP. In both subfigures C and D, scout-interpolation and scout-reconstruction results using seven scout views are shown. The reconstruction profiles for both scout-assisted methods match with the ground truth at all truncation ratios. Also the residuals for scout-interpolation and scout-reconstruction w.r.t. the ground truth were plotted in Figs. 5E and F respectively. The residuals for both these methods lie in the sub 1% range.

Next the relative root mean square error (RRME) between reconstruction of truncated sinogram and ground truth was calculated according to (Tang et al. 2009). The area in which RRME was calculated, corresponds to the ROI of sinogram truncation ratio of 0.8, and is shown in Fig. 6A inset. The error values were plotted in Fig. 6A. Among the four reconstruction algorithms, truncated-FBP has the highest error. While the error by truncated-FBP is low at smaller truncation ratios, RRME becomes significant when the truncation ratio is higher than 0.5. RRME for SS-SART-TV is always lower than for truncated-FBP. RRME is almost negligible when using scout-interpolation or scout-reconstruction, and this is true at all truncation ratios.

Within the scout-interpolation scheme, if the start-angle (or end-angle) of the scout views is higher than (or lesser than) the start-angle (or end-angle) of the interior scan, extrapolation needs to be carried out in Step (ii) of Sec. 2.4.3. It was observed that the extrapolation step is more prone to error (an example of erroneous extrapolation is marked by an arrow in Fig. 2E). In case of a tomography acquired over an angular range of 360° , the periodicity of the sinogram can be exploited to reduce such errors. However most scans in this study were acquired over a short-scan range (Parker 1982) (see Tab. 1), and such periodicity could not be exploited. As a simple alternative to reduce the extrapolation errors, the start- and end-angles of the scout views may be selected as close to the corresponding values for the interior scan as possible.

3.1.2. Number of scout views—In the next study, the number of scout views was varied between two and eight, while keeping the truncation ratio constant at 0.7. RRME for scout-interpolation and scout-reconstruction methods are plotted in Fig. 6B. Even with two scout views, the RRME by scout-assisted methods (0.0021 for scout-interpolation, and 0.0036 for scout-reconstruction, see Fig. 6B) is far lower than the corresponding value for truncated-FBP (0.6836, see Fig. 6A).

For the scout-interpolation method, the RRME, in general, decreases with more scout views. But an abrupt change in this trend is observed at four scout views. This is attributed to the variability in interpolation depending on scout locations. For the scout-reconstruction method, the RRME always decreases when more scout views are available. This shows that scout-reconstruction method is more robust and stable than scout-interpolation. For both methods, though two scout views significantly reduce the RRME when compared with truncated-FBP, the RRME falls by another degree of magnitude when five or more scout views are used.

3.2. Results: Interior micro-CT phantom II

The scan of the second interior micro-CT phantom of Fig. 1B provides real interior projections. In this case, the center of rotations of interior and global scans are completely different. Thus, the scout-interpolation method of Sec. 2.4.3 is not applicable here. Only the scout-reconstruction method was tested for this sample.

Firstly, the reconstruction of the global scan cropped to the ROI of the interior scan is shown in Fig. 7A. The image was up-sampled at the pixel width of high-resolution interior scan to allow easier comparison. Using the truncated-FBP algorithm, interior projections were

reconstructed to yield Fig. 7B. A cupping artifact around the edges is easily observed. Finally, scout-reconstruction method of Sec. 2.4.4 was applied using 2, 4, 7, or 100 global scout views. Fig. 7C is reconstructed by using seven global scout views – there is almost no cupping artifact.

Line profiles across the dotted line in Fig. 7A are plotted in Fig. 7D for global FBP, truncated-FBP, and scout-reconstruction using 2, 4, 7, and 100 global scout views. The line plots show that truncated-FBP does not match global FBP, while scout-reconstruction does. This plot also demonstrates the variation in scout-reconstruction results when using different number of scout views. Even with two scout views, the line profile is almost identical to global FBP value. There is a minor change in the line profile as number of scouts is increased to four. When seven scout views are used, the line profile stabilizes, and is identical to scout-reconstruction result using 100 scout views.

In the following studies (sections 3.3 and 3.4), seven scout views are used as additional information. As seen in Fig. 7D, this allows reduction of DC bias and cupping artifact, while posing a very minor scanning overhead.

3.3. Results: Rock sample

The rock sample was scanned globally at $3.4\ \mu\text{m}$ detector pixel size, followed by an interior scan at $1.4\ \mu\text{m}$ detector pixel size. The global sinogram was reconstructed by traditional FBP. The interior ROI was cropped out and up-sampled to pixel width of interior scan in the same way as Sec. 3.2; the resultant image is shown in Fig. 8A. Next, the result of truncated-FBP is shown in Fig. 8B, where a DC bias and cupping artifact are clearly visible.

Axis of rotation of interior and global scans were identical for this sample. However Tab. 1 shows that the source-to-rotation axis distances are different –19 mm in the global scan, and 8 mm in the interior scan. Ideally, the scan setting of Fig. 3A is not obeyed, and as such, the scout-interpolation method cannot be employed. However the main role of the scout views is to provide realistic projection values just outside the truncated projection data. As a very rough approximation, the global projections acquired at 19 mm were used as scout views to extrapolate the interior projections acquired at 8 mm. This approximation was possible mainly because the axes of rotation were identical. The reconstructed slice is shown in Fig. 8C, and no cupping artifacts were observed. Finally, the scout-reconstruction algorithm was employed, and the reconstructed slice is in Fig. 8D. No cupping artifact was observed.

Profiles were taken across the line marked in Fig. 8A, and plotted in Fig. 8E. When compared with the global reconstruction line profile, the cupping artifact of truncated-FBP is evident around the left and right edges of the plot. Both the scout-interpolation and scout-reconstruction methods provided a much better match to the global reconstruction, though exact feature-to-feature correspondence does not exist. An exact feature-to-feature correspondence was observed in Fig. 7D for the interior phantom II because it had very coarse and regular features. For the rock sample, such an exact correspondence is not possible to achieve because the global scan is carried at much lower resolution than the interior scan, and the sample contains highly detailed features.

3.4. Results: Mouse lung

For the mouse lung sample of Fig. 1D, the global sinogram was reconstructed by traditional FBP, and the interior ROI (after up-sampling to the pixel size of the interior scan) is displayed in Fig. 9G. In this image, the features inside the interior ROI are not clearly distinguishable because the resolution of the global scan is not sufficient to resolve the detailed features of the mouse lung.

The interior scan was performed at a different axes of rotation than the global scan. The scout-interpolation method was not applicable, and thus, truncated-FBP and scout-reconstruction methods were applied. Figures 9A and 9D show the reconstruction results by these two methods. Arrows in subfigures A and G mark the corresponding features that are only faintly discernible in the up-sampled global reconstruction (subfigure G). Figure 9H contains line profiles across line marked in subfigures A and D. The line plots do not show any significant difference in DC values between the two interior reconstruction methods. Also, no cupping artifact was observed by either of the reconstruction methods.

For better characterization of the results, further tests were carried out. The original interior sinogram (containing 988 detector pixels) was further truncated down to 814 and 648 detector pixels (i.e. reduced by 18% and 36% from original length, respectively). Truncated-FBP and scout-reconstruction methods were employed – the reconstructed slices are shown in subfigures B, C, E and F. Cupping artifact begins to appear in the truncated-FBP reconstruction when the detector length decreases to 648 pixels (see subfigure C, and the right edge of the corresponding line-plot in H). However, scout-reconstruction results do not show cupping artifact at any detector length, and hence this method is more robust than truncated-FBP. Overall, the artifacts due to truncated-FBP are much lower for this sample than for other samples in this study – this may be explained by the fact that the sample has no highly absorbing structures outside the FOV for the interior scan.

4. Conclusion and discussion

In this study, we introduced two methods that use only a small number of scout views to achieve accurate interior reconstruction. The scout-interpolation method (Sec. 2.4.3) is an extension of multi-resolution acquisition techniques (Pak-Kong Lun & Hsung 1997, Sahiner & Yagle 1995, Tisson et al. 2004). While it is only applicable to special scan configurations, it provides an extremely simple technique to achieve accurate interior reconstruction. The scout-reconstruction method (Sec. 2.4.4) combines compressed sensing based reconstruction (Yu & Wang 2009) with multi-resolution acquisition. This technique is more dynamic as it can be applied to multiple scan configurations. Scout-interpolation and reconstruction techniques were first verified on physical micro-CT phantoms that were specially fabricated for this study. The methods were then tested on two datasets from separate studies that could benefit from this new technique. In all cases except the lung sample, there was a major reduction of cupping artifacts and DC bias as compared to truncated-FBP. For the lung sample, scout-reconstruction and truncated-FBP provided similar reconstruction values for the original interior data. However, when the data was truncated even further, scout-reconstruction was shown to be more robust.

We demonstrated that five to seven scout views enabled accurate interior reconstruction in all the samples tested in this study. The phantoms and samples were designed or selected so that they posed a variety of challenges e.g. symmetric vs. asymmetric location of ROI, moderately attenuating vs. highly attenuating material etc. However certain samples may pose extremely limiting geometry or attenuation conditions, and require a higher number of scout views. While this remains a matter of further investigation, the number of scout views is still expected to be lesser than 20 (the number of views that has been shown to achieve sufficiently high image quality in various studies on sparse image reconstruction (Candès et al. 2006, Sidky et al. 2006, Yu & Wang 2010)).

The start- and end-angles (i.e. the angular range) of the scout views should be selected such that they provide the most relevant information for the two proposed methods. In Sec. 3.1.1, some guidelines for selecting these values for the scout-interpolation technique were noted. For the scout-reconstruction technique, acquiring scout views over the short-scan range of

($180^\circ + \text{fan-angle}$) (Parker 1982) is the optimum choice as this provides the most complimentary information in the SS-SART-TV step of Sec. 2.4.4 (Sidky et al. 2006). In the current study, these guidelines were obeyed, and high reconstruction accuracy was achieved. Only in case of the rock sample, scout views were acquired over the entire 360° , but the circular nature of the sample allowed high reconstruction accuracy without optimum sampling.

The run-times for the reconstruction algorithms described in Sec. 2.4 (truncated-FBP, scout-interpolation, scout-reconstruction and SS-SART-TV) were measured for the rock sample. The timing results, which are tabulated in Tab. 2, show that scout-interpolation and scout-reconstruction represent only a 6% and 23% overhead w.r.t. truncated-FBP, while SS-SART-TV is almost 47 times more time consuming than truncated-FBP. SS-SART-TV is the most time-consuming because it is a purely iterative reconstruction method, and works on all the interior projections acquired at a dense angular sampling. Within the scout-reconstruction method, there is a sub-step involving iterative reconstruction (Step (iii) in Sec. 2.4.4). But this sub-step uses only a handful of scout views, and is thus extremely quick. Also, in step (iv) of the scout-reconstruction method, the forward projection was performed on a sparse grid. This helped to sidestep the issue (pointed out in (Maaß et al. 2011)) of computational overload for a prohibitively large forward projection. Our implementation was not fully optimized, and future optimizations (e.g. through GPU implementation, TV minimization by soft-thresholding (Yu & Wang 2010)), would further reduce all runtimes.

Overall, the two new methods introduced in this study allow accurate interior reconstruction. Due to their low computational cost, these methods can be easily incorporated into commercial micro-CT scanners. These methods may be extended to industrial CT, or any imaging modality in which the scanner allows the acquisition of both global overview projections as well as high-resolution interior projections. Future research directions may include efforts to extend the scout-interpolation technique to arbitrary scan geometries e.g. by using “data-weighting” schemes similar to the one described in (Maaß et al. 2011).

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Figure 1.

Samples used in characterizing interior micro-CT. (A) Interior micro-CT phantom I. White arrows mark angular structures prepared by semiconductor fabrication techniques, and black arrows with white borders mark two of many micro-capillary tubes. (B) Interior micro-CT phantom II. (C) Rock sample. (D) Mouse lung. Interior scan ROI-s are marked by white squares. White cross-hairs depict the axis of rotation of global scans, while axis of rotation of interior scan passes through center of the white squares. The used detector pixel sizes are marked for global scans at top-right corner. For samples B, C and D, interior scans were acquired using $1.4\ \mu\text{m}$ pixel size detector. All scale bars are 1 mm.

Figure 2.

Sinograms of interior micro-CT phantom I demonstrating steps in interior reconstruction. (A) Global sinogram. (B) Truncated sinogram. (C) Truncated sinogram with six global scout views marked with white arrows. (D–F) Sinograms for the different reconstruction algorithms – (D) truncated-FBP (Sec. 2.4.1, borders of original sinogram marked by dotted lines), (E) scout-interpolation (Sec. 2.4.3), and (F) scout-reconstruction (Sec. 2.4.4). An example of erroneous extrapolation (Sec. 3.1.1) is marked by an arrow in subfigure E.

Figure 3.

Two configurations of high-resolution interior projections (P_H) w.r.t. low-resolution scout views (P_L). (A) is a special configuration where only the detector changes between interior and scout projections i.e. source-position (S_H and S_L), detector to rotation-axis distance, axis of rotation all remain constant. (B) is a more general configuration where interior and scout projections are acquired independently.

Figure 4.

Graphic depicting scout-reconstruction method of Sec. 2.4.4. (i) High-resolution interior scan (P_H) is acquired from source position S_H . (ii) A set of scout views (P_L) is acquired from source position S_L . (iii) SS-SART-TV is carried out on scout views P_L . (iv) Reconstructed image is forward projected in high-resolution geometry to get sinogram P_{LH} . (v) P_{LH} and P_H are merged before (vi) final reconstruction step by FBP.

Figure 5.

Horizontal line profiles across line marked in subfigure C, for various truncation ratios and for various interior reconstruction algorithms – (A) truncated-FBP, (B) SS-SART-TV, (C) scout-interpolation, and (D) scout-reconstruction. (E) and (F) plot residuals of subfigures C and D respectively, w.r.t. ground truth. Legend in B corresponds to A, B, E and F; legend in D corresponds to C and D (plots in C and D have been drawn thicker to highlight the fact that all profiles overlap).

Figure 6.

For the interior micro-CT phantom I, relative root mean square error (RRME) w.r.t. global FBP was calculated across ROI marked by square. (A) RRME at different truncation ratios for different algorithms. Number of scout views used is seven in each case. (B) RRME with different number of scout views (at fixed truncation ratio of 0.7) for scout-interpolation and scout-reconstruction. The y-axis in two graphs are scaled differently.

Figure 7.

Interior reconstruction results of interior micro-CT phantom II. (A) Interior ROI from FBP of low-resolution global scan is up-sampled to pixel-size of high-resolution interior scan, and serves as a reference. Interior ROI reconstructed by (B) truncated-FBP, and (C) scout-reconstruction method. (D) Line plots comparing truncated-FBP, scout-reconstruction, and global FBP. Line plots also show variation in scout-reconstruction result when available number of scout views is 2, 4, 7, or 100.

Figure 8.

Results on rock sample. (A) Interior ROI from FBP of low-resolution global scan is up-sampled to pixel-size of high-resolution interior scan, and serves as a reference. Reconstruction of interior ROI by (B) truncated-FBP, (C) scout-interpolation, and (D) scout-reconstruction techniques. (E) Plot of line profiles across white dotted line in subfigure A.

Figure 9.

Tomographic reconstruction of mouse lung sample. Reconstruction of interior ROI by (A) truncated-FBP, (D) scout-reconstruction, and (G) global FBP (after up-sampling to pixel size of high-resolution scan). In subfigures A and G, arrows mark corresponding features. Interior sinogram, originally 988 detector pixels long, was further truncated down to 814 and 648 pixels. Truncated-FBP and scout-reconstruction methods were applied at the different detector lengths, and the corresponding reconstructed slices are shown in subfigures B, C, E, and F. (H) Plot of line profiles across white dotted lines in subfigures A, C, D, F.

Settings for scans acquired on Xradia MicroXCT-400 scanner (RA = rotation axis, meas. = measurement). Four samples (A) – (D) correspond to samples in Fig. 1.

Table 1

Scan Parameters	(A) Phantom I		(B) Phantom II		(C) Rock		(D) Lung	
	G	i	G	i	G	i	G	i
Global (G)/Interior (i)								
Detector pixel size (μm)	27	1.4	27	1.4	3.4	1.4	27	1.4
Binning	2	2	2	2	1	1	1	2
Number of detector pixels	1024	998	1024	998	2022	2006	2048	998
Source-RA distance (mm)	26.0	26.0	26.0	26.0	19.0	8.0	59.9	55.0
Detector-RA distance (mm)	164.9	99.9	99.9	30.0	5.5	5.5	64.7	18.0
Field-of-meas. (dia., mm)	7.60	11.53	1.24	5.20	1.58	26.87	2.01	
X-ray energy (kV)	40	60	60	70	65	40	40	
Current (μA)	100	100	100	85	83	200	200	
Exposure time (sec)	3.0	0.5	20.0	2.2	3.4	1.8	8.0	
Start angle (degrees)	-101	-107	-92	-180	-180	-107	-92	
End angle (degrees)	101	107	92	180	180	107	92	
Number of projections	1500	1500	1500	1800	2700	1648	1228	

Table 2

Algorithm run-times (normalized w.r.t run-time of truncated-FBP).

Algorithm	Trunc. FBP	Scout-interp.	Scout-recon	SS-SART-TV
Run time (sec.)	116.44	123.45	142.89	5527.32
Run time (normalized)	1.00	1.06	1.23	47.47