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Region of interest reconstruction in x-ray fluorescence computed tomography for negligible attenuation

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Abstract

X-ray fluorescence computed tomography (XFCT) is a synchrotron-based imaging modality employed for mapping the distribution of elements within slices or volumes of intact specimens. A pencil beam of external radiation is used to stimulate emission of characteristic X-rays from within a sample, which is scanned and rotated through the pencil beam in a first-generation tomographic geometry. One limitation of XFCT is the long image acquisition time required to acquire a complete set of line integrals one-by-one. Typically, even if only a portion of a slice through the object is of interest, measurement lines are acquired spanning the entire object at every projection view over 180 degrees to avoid reconstructing images with so-called truncation artifacts. In this work, we show that when attenuation is negligible, recent developments in tomographic reconstruction theory can be used to reduce the scanning effort required to reconstruct regions of interest within the slice. The new theory provides explicit guidance as to which line integrals must be measured for a given ROI and also provides a backprojection-filtration reconstruction algorithm that averts the truncation artifacts that typically plague filtered backprojection reconstructions from truncated data. This is demonstrated through simulation studies and with real synchrotron-based XFCT data.

Keywords

X-ray fluorescence computed tomography; image reconstruction; region-of-interest reconstruction

I. Introduction

A. Current approaches to XFCT data acquisition

Synchrotron-based X-ray fluorescence imaging techniques are being used with increasing frequency for the mapping and chemical speciation of trace metals in geological, environmental, and biological samples [1]. There are three principal approaches to such imaging: scanning X-ray fluorescence (XRF) imaging, confocal XRF imaging, and X-ray fluorescence computed tomography (XFCT). In scanning XRF, the specimen is sectioned into thin slices that are scanned through a focused synchrotron beam which stimulates emission of characteristic X-rays [1]. These characteristic X-rays are detected with an external detector and mapped into an image, which is assembled pixel-by-pixel as the specimen is scanned through the beam. In confocal XRF, the acquisition is similar but the object is not sectioned [2]. Instead, polycapillary optics are used on detection to focus the attention of the external fluorescence detector at a particular depth in the sample. The stimulating beam is also focused to the same depth to achieve confocal sensing. Finally, in XFCT an image of a selected slice through an unsectioned object can be obtained through the use of a tomographic acquisition and reconstruction strategy [3], [4], [5]. A pencil beam

of synchrotron radiation is used to illuminate a line through a sample, stimulating emission of characteristic X-rays. These provide information about the line integral of the concentration of the element along the line traversed by the stimulating pencil beam, suitably modified to account for attenuation of the incident and fluorescent photons in the sample. To obtain sufficient tomographic data to reconstruct the two-dimensional distribution of elements in a single slice through the object, the specimen is typically scanned line by line through the beam at each of a number of projection angles.

One purported advantage of the scanning XRF and confocal XRF techniques over the XFCT technique is their ability to selectively scan only a region of interest (ROI) of the slice in question. In XFCT, while it is currently possible to selectively scan only the slices of interest, the acquired measurement lines typically span the entire object at every projection view over 180 degrees to avoid reconstructing images with so-called truncation artifacts. This is done even when only a portion of the slice is truly of interest. However, recent developments in tomographic reconstruction theory have shown that it is possible to obtain exact reconstruction of ROIs from truncated line integral projections [6], [7]. When attenuation and self-absorption are negligible in XFCT, the measured data can be approximated as line integrals. Thus, in this paper, we show how these new ideas can be applied to devise minimum-data scanning trajectories to speed acquisition in XFCT under the assumption of negligible attenuation and also to implement and characterize reconstruction algorithms capable of reconstructing accurate images from these data. While the reconstruction theory presented in this paper is not new, XFCT represents a very natural application of these new minimum-data requirements since the first-generation data-acquisition scheme allows total flexibility in choosing which line integrals are measured, unlike in computed tomography, for instance, where complex collimation systems would be needed to alter the object illumination. Moreover, XFCT currently suffers from long scan times, so the ability to reduce scanning effort by focusing on an ROI could be of great practical significance.

B. Potential biomedical applications of XFCT

X-ray fluorescence computed tomography (XFCT) has a wide variety of potential applications involving mapping of trace metals in biological samples. The improved ability to map the distribution and chemical species of metal ions in biological samples would greatly benefit a wide variety of research efforts aimed at understanding the role of metal ions in health and disease. One third of all known proteins contain metal cofactors, and many of these proteins are metalloenzymes that catalyze crucial biochemical reactions [8]. It is not well understood where metal ions are stored before being incorporated into metalloproteins, nor where they go after protein degradation [1]. These questions could be clarified using XFCT.

The intracellular concentration and distribution of metals appears to be carefully regulated in normal tissue, and their dysregulation is known to contribute to a number of degenerative diseases, including amyotrophic lateral sclerosis, Alzheimer's disease and Parkinson's disease [9], [8]. Trace metals appear also to play a significant role in angiogenesis, and a recent study employed 2D scanning mode X-ray fluorescence to reveal large-scale relocation and extracellular translocation of cellular copper during angiogenesis [10].

Finally, there is great interest in using synchrotrons to map the distribution of exogenous metal-containing agents and nanoparticles used for imaging and therapy. Endres *et al.* employed scanning mode XRF to assess the ability of four Gd-based MRI contrast agents to cross the cell membrane [11], while Paunesku *et al.* used the technique to determine subcellular localization of TiO₂-oligonucleotide nanocomposites and demonstrated that they were indeed colocalized with their targets, the nucleolei [12].

It is worth noting, of course, that since synchrotron-based XFCT is often practiced with as many as 10^{11} photons/s in a $5\text{--}10\text{ }\mu\text{m}^2$ spot, dose and sample damage considerations must be taken into account when preparing samples or considering imaging of live subjects.

II. Methods

A. Background on XFCT imaging

The acquisition geometry of XFCT is depicted in Fig. 1(a). The pencil beam of X-rays originates from the bottom of the figure. As the beam travels through the object, it undergoes photoelectric interactions with inner shell electrons of atoms in the sample; these atoms, in turn, emit isotropically distributed characteristic X-rays that can be detected by the energy-sensitive (but not position-sensitive) fluorescence detector.

Typical dwell times per line-integral measurement are on the order of 0.5s–1.5 s. The object is then scanned through the beam, line by line, and then rotated, as the line-by-line scan of the object must be repeated at dozens of projection views over 180° or 360° to obtain the data necessary for image reconstruction. The entire process currently takes well over an hour for typical samples.

In the absence of attenuation, the height of each spectral peak acquired for a given illumination line would correspond to the line integral through the corresponding element's distribution along that line. The scanning and rotation would provide samples of the *Radon transform* of the elemental distributions. The Radon transform is the well-known line integral mapping that underlies medical CT, and it can be readily inverted by simple algorithms such as filtered backprojection (FBP) [13] when a complete set of samples is acquired.

The notation is illustrated in Fig. 1(b), where the $\{\xi, \eta\}$ coordinate system is fixed in the laboratory space, while the $\{x, y\}$ coordinate system, fixed to the object, is rotated clockwise relative to the $\{\xi, \eta\}$ coordinate system by an angle φ in the $\xi - \eta$ plane [14], [15]. We denote the density, in g/cm^3 , of an element of interest by $\rho^{rot}(\xi, \eta)$ in the $\{\xi, \eta\}$ coordinate system and simply by $\rho(x, y)$ in the $\{x, y\}$ coordinate system. These two quantities are related by

$$\rho^{rot}(\xi, \eta) = \rho(\xi \cos \varphi - \eta \sin \varphi, \xi \sin \varphi + \eta \cos \varphi). \quad (1)$$

Thus, with an object rotation φ and displacement ξ , the mean number $\bar{y}(\xi, \varphi)$ of counts under the K_α peak measured by the fluorescence detector per second per cm^2 of incident beam profile will be given, in the absence of significant attenuation, by

$$\bar{y}(\xi, \varphi) = I_0 \tau_p \omega_K \nu_\alpha \varepsilon \frac{\Omega}{4\pi} \int_{-\infty}^{\infty} \rho^{rot}(\xi, \eta) d\eta, \quad (2)$$

which can be obtained by omitting the attenuation factors from equation 2 in our Ref. [15], which is based on equation 5 from [16].

Of the constants before the integral, I_0 is the intensity of the flux rate of the stimulating beam in $\text{photons cm}^{-2} \text{ s}^{-1}$, τ_p is the photoelectric mass attenuation coefficient in cm^2/g for the element of interest at the incident beam energy, ω_K is the K -shell fluorescence yield, ν_α is the branching ratio for the K_α line, ε is a detector efficiency factor, and Ω is the solid angle

subtended by the fluorescence detector. To get pure line integral data we need simply normalize by the factors in front of the integral (in practice this is usually done using a calibration standard). Thus we obtain data

$$p(\xi, \varphi) \equiv \frac{\bar{y}(\xi, \varphi)}{I_0 \tau_p \omega_K \nu_\alpha \varepsilon_{\frac{9}{4\pi}}} = \int_{-\infty}^{\infty} \rho^{rot}(\xi, \eta) d\eta \quad (3)$$

B. PI-line reconstruction for negligible attenuation

The newly derived tomographic data-sufficiency conditions apply to measurements that are the line integrals of the distribution being reconstructed. As shown above, XFCT measurements are well modeled as line integrals when the attenuation suffered by the incident beam and fluorescent photons are negligible. While X-ray attenuation is often a significant factor in XFCT, it can be negligibly small in some situations of practical interest, such as imaging of high-Z elements in small biological specimens. Moreover, while the theory to be presented is exact only in the case of negligible attenuation, it provides a basis for excellent approximate algorithms in the case of significant attenuation. These are discussed below in Sec. II-C.

The newly derived data-sufficiency condition relies on the important concept of a PI-line. For a point source of X-rays revolving around an object in a circular trajectory, a PI-line is simply a straight line connecting two points on the source trajectory. In the case of parallel-beam illumination, the source is effectively at infinity, and the vertical lines in Fig. 2(left) are one possible set of parallel-beam PI-lines intersecting the ROI shown. The new data-sufficiency condition says simply that to reconstruct the image values along a desired set of PI-lines, the parallel-beam illumination must fully cover the intersection of the PI-lines and the object support [6], [7]. This implies that it is possible to reconstruct a portion of an object from truncated data. This is illustrated in Fig. 2(left), which shows the scanning range necessary at a variety of projection angles. This can mean a substantial reduction in the number of measurements required, as illustrated in 2(right), which shows that only a portion of the usual measurement space needs to be sampled.

The PI-Line reconstruction scheme involves reconstructing images on the PI-lines themselves. In a parallel-beam geometry, with the source effectively at infinity, the theoretical PI-lines are infinitely long. In practice, however, we need only concern ourselves with the intersection of the PI-lines with the compact support of the slice being imaged, which can be assumed to be circular without loss of generality. In this case, a PI-line is just a chord connecting any two points on the circle. We will characterize the PI-line by its perpendicular distance l from the origin and by the angle α between this perpendicular and the x axis, as shown in Fig. 3. If we let x_π denote the distance along the PI-line from the intersection with the perpendicular, then the relationship between the fixed coordinates and the PI-line coordinates is given by

$$\begin{aligned} x &= l \cos \alpha - x_\pi \sin \alpha \\ y &= l \sin \alpha + x_\pi \cos \alpha. \end{aligned} \quad (4)$$

Assuming a compact support corresponding to a circle of radius R , for a specified l , the coordinate x_π can vary between $x_{\pi_0} \equiv -\sqrt{R^2 - l^2}$ and $x_{\pi_1} \equiv \sqrt{R^2 - l^2}$.

Assume we measure a set of parallel-beam data $p(\xi, \varphi)$ for an appropriate range of ξ and φ . To reconstruct an image on the PI-line specified by a particular pair l and α with x_π ranging from $x_{\pi 0}$ to $x_{\pi 1}$, we first calculate an intermediate function

$$g_\pi^{(para)}(x_\pi, l, \alpha) = \int_\alpha^{\alpha+\pi} d\varphi \frac{\partial p(\xi', \varphi)}{\partial \xi'}, \quad (5)$$

where ξ' is given by

$$\xi' = l \cos(\alpha - \varphi) - x_\pi \sin(\alpha - \varphi). \quad (6)$$

The reconstruction along the PI-line is then given by

$$f_\pi(x_\pi, l, \alpha) = \frac{1}{2\pi^2} \frac{1}{\sqrt{(x_{\pi 0} - x_\pi)(x_\pi - x_{\pi 1})}} \left[PV \left\{ \int_{x_{\pi 0}}^{x_{\pi 1}} dx'_\pi \frac{\sqrt{(x_{\pi 0} - x'_\pi)(x'_\pi - x_{\pi 1})}}{x_\pi - x'_\pi} g_\pi^{(para)}(x'_\pi, l, \alpha) \right\} + 2\pi p(l, \alpha) \right], \quad (7)$$

where PV means the result of the integral is to be understood as the Cauchy principal value [6], [7].

This algorithm has a backprojection-filtration structure and we refer to it as the BPF algorithm. After reconstruction of the set of PI-lines spanning the ROI, the results are rebinned into Cartesian coordinates for display.

C. PI-line reconstruction for significant attenuation

In the presence of significant attenuation, XFCT measurements no longer represent strict line integrals through the distribution of interest and the methods presented above are no longer exact. Noo *et al.*, however, have shown that exact reconstruction from truncated data is possible in 2D parallel-beam single-photon emission computed tomography (SPECT), which has a very similar imaging model to XFCT [15], when the attenuation is known and uniform within a convex region that includes all activity sources [17]. The question of whether exact reconstruction from truncated data is possible in XFCT (or SPECT) in the presence of *non-uniform* attenuation is still open.

A simple approximate approach to performing ROI reconstruction in the presence of attenuation is to use the PI-line based algorithms above to provide an initial reconstruction, and then to apply an image-space correction method such as the one described by Hogan [4] and extended by Miqueles and De Pierro [18]. Finally, a more sophisticated approach could involve applying fully iterative reconstruction, which has been widely used in XFCT for complete data problems [16], [19], [20], [21], [22]. However, there are significant challenges involved in applying iterative reconstruction to truncated data ROI problems since one must typically compare the reprojection of the current image estimate to the measured data, and such reprojections would require information about portions of the object outside the ROI that can be reconstructed from the truncated data.

III. Results

A. Simulated data

To demonstrate the potential for ROI imaging in XFCT, we first generated simulated XFCT measurement data of a numerical phantom. It comprised an outer ellipse of attenuating matrix (modeled to be cellulose of density 0.8 g/cm^3) and three inner ellipses made of 0.1 g/cm^3 calcium, iron, and zinc, respectively. The outer ellipse had major axis $608 \mu\text{m}$ and minor axis $384 \mu\text{m}$. The inner ellipses had major axis $544 \mu\text{m}$ and minor axis $64 \mu\text{m}$. We also consider a variation of the phantom in which a dense (1 g/cm^3) zinc sphere of diameter $128 \mu\text{m}$ is placed just outside the region of interest. The two phantoms are shown schematically in Fig. 4. Using the forward model described previously [21], which includes the effects of incident beam and fluorescent photon attenuation, we simulated complete transmission and fluorescence sinograms of 128 views spanning 180 degrees and 128 $5\text{-}\mu\text{m}$ translations per view. We assumed an incident beam energy of 20 keV, and fluorescence emission energies of 3.691 keV, 6.403 keV, and 8.638 keV for calcium, iron, and zinc, respectively. The attenuation map linear attenuation values at the various energies of interest were calculated by use of the NIST XCOM program.¹ They are listed in Table I. The beam width was modeled as $5 \mu\text{m}$. The complete transmission sinogram is shown in Fig. 5(a). Based on the pi-line theory, we then identified the subportion of the sinogram needed to reconstruct the upper 25% of the phantom. Fig. 5(b) shows this reduced sinogram, which could be acquired more quickly in a line-by-line acquisition strategy than the sinogram on the left. This reduced sinogram involves 67.5% of the line integrals acquired in the full sinogram.

We reconstructed images of the ROI by use of the PI-line based BPF algorithm described above as well as the conventional FBP algorithm. The results are shown in Fig. 6, where the BPF algorithm is labeled “PI-line ROI trunc data” and the FBP algorithm applied to the truncated data is labeled “FBP ROI trunc data” For reference, the same region extracted from the FBP reconstruction from the full dataset (labeled “FBP ROI full data”) is also shown. We did not correct for attenuation.

The PI-line BPF reconstruction from truncated data produces images that are nearly identical to the FBP reconstruction from the full dataset. The FBP reconstruction from the truncated dataset reveals some artifactual brightening near the boundary of the ROI. This is most visible in the transmission map reconstruction and in the zinc reconstruction for the second phantom, which contains a large dense zinc object just outside the ROI. This artifactual brightening in the FBP image can be confirmed by plotting the vertical profile through the reconstructed zinc ellipse from the boundary of the ROI toward the top of the phantom. These are shown in Fig. 7, where it can be seen that the PI-Line reconstruction from the truncated data agrees perfectly with the FBP reconstruction from the full dataset while the FBP reconstruction from the truncated data overestimates the zinc concentration (grossly so, for the second phantom).

B. Real data

We also applied the strategy described in this paper to perform ROI reconstruction of XFCT data obtained at the GeoSoilCars (GSECARS) beamline at Argonne National Laboratory’s Advanced Photon Source (APS). The sample was a leaf of the plant *Alyssum murale* “Kotodesh,” which is a known nickel hyperaccumulator that was being studied to determine distribution of Ni and other trace metals [23]. The beam energy employed was 11 keV with a width of $2 \mu\text{m}$; 212 samples were acquired for each sample rotation position with a $2 \mu\text{m}$

¹<http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html>

sampling interval. The angular sampling interval was 2° over 180° . Energy windows of 200 eV in width were centered around the K_α peaks of Ca (3.7 keV), Mn (5.9 keV), Fe (6.4 keV), Ni (7.5 keV), and Zn (8.6 keV).

This was an existing dataset, and was thus complete, with no truncation in any view. This allowed us to artificially truncate the data as needed for reconstruction of specified ROIs while still having the complete data needed for accurate reconstruction for the purposes of comparison. From a preliminary FBP reconstruction, we then identified a region of interest representing the top 37% of the leaf. Using the PI-line framework, we identified the subportion of the sinogram needed to reconstruct the ROI. This reduced sinogram involves 74% of the line integrals acquired in the full sinogram. The complete and truncated zinc sinograms are shown in Fig. 8(a) and (b).

We then reconstructed by use of the PI-line based BPF algorithm described above as well as the conventional FBP algorithm. The results are shown in Fig. 9, where the BPF algorithm is labeled “PI-line” and the FBP algorithm applied to the truncated data is labeled “FBP trunc.” For reference, the same region extracted from the FBP reconstruction from the full dataset (labeled “FBP full”) is also shown. The PI-line BPF reconstruction from truncated data produces images that are exactly equal to the BPF reconstruction from the complete data in the ROIs. The FBP reconstruction from the truncated dataset reveals some artifactual brightening near the boundary of the ROI as we have seen in the phantom data. The reconstructed values in the ROI itself are also inaccurate, with the inaccuracy growing larger as one approaches the boundary. This can be seen in Fig. 10(Left), which provides surface plots of the percent difference between the truncated FBP Zn reconstruction and the full FBP reconstruction in the ROI. The errors approach 10% at the boundary of the ROI. These are typical of the results seen for other elements, with the exception of Mn, where the difference is dominated by a spike at the hotspot near the edge of the ROI. For comparison, we show in Figure 10(right) the difference between the truncated Pi-Line Zn reconstruction and the full FBP reconstruction in the ROI. They do not agree perfectly due to numerical differences and interpolation errors, but there is no systematic bias toward the edge of the ROI as was seen in the truncated FBP reconstruction. As mentioned above, the truncated Pi-line reconstruction agrees perfectly with the full-data Pi-line reconstruction in the ROI.

IV. Conclusions and Discussion

We have demonstrated that recent developments in tomographic reconstruction theory allow for the quantitatively accurate reconstruction of regions of interest in XFCT from minimal, truncated datasets when attenuation and self-absorption are negligible. The new theory provides explicit guidance as to which line integrals must be measured for a given ROI and also provides a BPF-style reconstruction algorithm that averts the truncation artifacts that typically plague FBP-style reconstructions from truncated data.

The time savings, while substantial if only the ROI is truly of interest, is not as large as the reduction in the reconstructible area of the image (i.e., an ROI representing 25% of the full field of view requires substantially more than 25% of the full sinogram for reconstruction). The potential time savings depends somewhat on the specific geometry of the region of interest. Reconstructing the tip of a long, thin object like the leaf required relatively less of the sinogram than reconstructing the tip of the shorter, wider phantom. As seen in the example provided here, ROIs representing 25% and 37% of the object required 67.5 and 74% of the full sinogram, respectively, for reconstruction. One can imagine using this strategy by first performing either a full resolution transmission scan (which can generally be performed quickly due to the better Poisson statistics) or a coarse tomographic fluorescence scan of the element of interest. From either of the images, one could then

identify a region of interest and use the framework presented here to determine the scanning geometry needed to measure the needed line integrals.

The results presented here focused on the case where fluorescence attenuation is negligible. We are currently examining the use of post-correction algorithms to allow for ROI imaging even in the face of strong attenuation, as discussed in Sec. II-C. It is perhaps worth mentioning, however, that the ROI reconstruction strategy gives one the ability to minimize attenuation effects, by focusing on, for example, just the tip of an extended object. One could then wisely choose the orientation of the object during scanning so as to temper attenuation effects.

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Figure 1.

(a) Acquisition geometry for XFCT. A pencil beam of X-rays originates from the bottom of the figure and stimulates emission of characteristic X-rays from all the pixels in the column shown. Such fluorescent photons are seen emerging from a particular pixel and travelling toward the detector. (b) Illustration of notation used. The $\{\xi, \eta\}$ coordinate system is fixed in the laboratory space, while the $\{x, y\}$ coordinate system, fixed to the object, is rotated clockwise relative to the $\{\xi, \eta\}$ coordinate system by an angle ϕ in the $\xi - \eta$ plane. The data measured for the illumination line shown is thus associated with the parameters ξ and ϕ and is denoted $y(\xi, \eta)$.

Figure 2.

(left) Illustration of the scan requirements for the ROI shown filled with vertical lines. These lines represent the PI-lines on which image reconstruction will take place. The data sufficiency condition says that all line integrals intersecting this set of PI-lines must be measured. The resulting scan requirements for three different projection angles are illustrated. (right) Illustration of the subset of sinogram data required under the minimum data scheme.

Figure 3.

Parametrization of a PI-line. It is characterized by its perpendicular distance l from the origin and by the angle α between this perpendicular and the x axis. x_π denotes the signed distance along the PI-line from the intersection with the perpendicular.

Figure 4.
Schematics of the two phantoms used in the simulation studies.

Figure 5.
(a) Complete transmission sinogram for the phantom of interest. (b) Portion of transmission sinogram needed to reconstruct the region of interest.

Figure 6.

Reconstructions of the various elemental components, as well as the transmission map, of the two phantoms by use of the methods being compared. (a) The basic phantom. (b) The alternative phantom with an additional zinc-rich object just outside the ROI. Each set of elemental images is scaled to the maximum value in the three images, and the resulting gray scale used is: Ca [0–0.0066], Fe [0–0.047], Zn [0–0.11], Trans. [0–9.16].

Figure 7.
Vertical profile through the zinc ellipse in the two phantoms under consideration.

Figure 8.

(a) Complete zinc sinogram for the leaf. (b) Portion of zinc sinogram needed to reconstruct the region of interest.

Figure 9.

Reconstructions of leaf tip ROI by use of the PI-line algorithm from minimal, truncated data (labeled “PI-line”) by FBP from minimal, truncated data (labeled “FBP Trunc”) and by FBP from full data (labeled “FBP Full”). Each set of elemental images is scaled to the maximum value in the three images, and the resulting gray scale used is: Ca [0–1050.0], Cu [0–31.6], Fe [0–207.5], Mn [0–35.9], Zn [0–61.8], Ni [0–174.8].

Figure 10.

(Left) Surface plot of the percent difference between the truncated FBP Zn reconstruction and the full FBP reconstruction in the ROI. (Right) Surface plot of the percent difference between the truncated Pi-line Zn reconstruction and the full FBP reconstruction in the ROI. The contours shown above the surfaces are the zero contours which allow for discernment of the shape of the leaf.

Table I

Densities and attenuation coefficients of phantom materials at energies of interest

Material	Density (g/cm ³)	Attenuation coefficient (cm ⁻¹)			
		3.691 keV	6.403 keV	8.638 keV	20.0 keV
Cellulose	0.8	63.8	12.2	5.0	0.5
Zinc	0.1	47.8	10.8	4.8	3.7
Iron	0.1	31.9	7.1	25.1	2.6
Calcium	0.1	15.2	31.4	14.0	1.31