CALIBRATIONS FOR ANALYZING INDUSTRIAL SAMPLES ON MEDICAL CT SCANNERS

Patricia K. Hunt, Philip Engler, and
William D. Friedman

BP American Research and Development
4440 Warrensville Center Road
Cleveland, Ohio 44128

INTRODUCTION

Computed tomography (CT) is a non-destructive technology that produces an image of an internal slice through a sample via the reconstruction of a matrix of X-ray attenuation coefficients [1,2]. An imaged slice can be divided into an n x n matrix of voxels (volume elements). The attenuation of N_o X-ray photons passing through any single voxel having a linear attenuation coefficient μ reduces the number of transmitted photons to N according to Beer's Law:

$$N = N_o \exp(-\mu x)$$

where x is the dimension of the voxel in the direction of the X-rays. Material parameters that determine the linear attenuation coefficient of a voxel include its density ρ and mass attenuation coefficient μ^*:

$$\mu = \mu^* \rho$$

Mass attenuation coefficient, in turn, depends on the atomic number of the material and the photon energy of the beam. For multi-component voxels, the atomic number dependence is weighted by the volume fraction of each component (partial volume effect). Thus the composition and density of the material in a voxel will determine its linear attenuation coefficient. A convention in medical imaging is to normalize the measured linear absorption coefficient to that of water:

$$\text{CT number} = \frac{\mu(\text{material}) - \mu(\text{water})}{\mu(\text{water})} \times 1000$$

Commonly used in the medical field since the early 1970's, CT more recently has been applied to materials analysis. Because they are readily commercially available, medical CT scanners are often used to analyze industrial samples. A complete discussion of the advantages and disadvantages of the different generations of medical scanners available for industrial use is presented in the literature [3,4,5].

The usage of medical instruments in industry gives rise to several problems due to the fact that medical scanners and corresponding reconstruction algorithms are customized to human samples whose size, shape, density, and composition vary from industrial samples. Presented in this paper are calibrations for obtaining meaningful CT data for industrial samples using medical scanners. Calibrations were made using a second generation, dual slice Technicare Deltascan 100 scanner with a tungsten source, seven BGO detectors (three per slice plus one reference), a DEC PDP 11/04 computer system, and a set scan circle size of 11.4 inches. The unit operates at a tube current and voltage of 120 KV and 25 mA, respectively. While some calibrations are specific to the Deltascan 100, others can be applied to most medical instruments.

Two types of calibrations are presented: 1) those that involve changes only to the sample; and 2) those that involve changes to the scanner and scanner software. The first type is necessary for cases in which a leased or rented scanner that cannot be modified is being used. Both types are useful for cases in which scanner modification is possible.

CALIBRATIONS INVOLVING ONLY THE SAMPLE

Images of industrial or geological samples obtained on medical instruments frequently show artifacts due to a phenomenon known as beam hardening. Beam hardening occurs when polychromatic X-ray sources are used, as is the case for medical CT scanners. It is due to a preferential absorption of the lower energy X-rays as they pass through the sample. If a monoenergetic source were used, beam hardening could not occur. Beam hardening induced artifacts include an apparent high density ring around the perimeter known as cupping. In addition, the measured attenuation coefficients are lower than the true values because the effective energy has shifted. These are problematic artifacts because their presence is not always obvious. Instrument manufacturers get around this problem by using compensating algorithms. But the algorithms have been optimized for the attenuation of X-rays by the human body and are not effective for materials having greater absorbing power. Thus, it is necessary to come up with other means of correcting for beam hardening in order to eliminate the problem.

One solution is to immerse samples in media having attenuating properties close to that of the sample. Cupping still occurs, but now it appears in the image at the perimeter of the immersion medium instead of the perimeter of the sample. Two immersion media that have yielded good results are sand and aqueous potassium iodide solution [4,5]. Sand immersion improves image quality, but, due to the heterogeneity of a sand pack, does not insure reproducible CT numbers. KI immersion both improves image quality and insures reproducible CT numbers.

While immersion works quite well for eliminating cupping and for creating conditions that yield reproducible numbers, it still does not address the problem of accuracy. Also, it is not always convenient, as with large samples or if rapid throughput is desired. Thus, other methods are required for eliminating beam hardening. As an alternative to sample immersion, procedures to modify the beam hardening correction software of the Deltascan 100 to be compatible with high density sample were implemented.

CALIBRATIONS INVOLVING THE SCANNER AND SCANNER SOFTWARE

As stated above, modifications to the Deltascan 100 were made to improve the beam hardening correction software. Additionally, modifications were made to improve a second problem with the Deltascan

100: its relatively low resolution compared to more modern CT instruments, which can resolve features that are 20-80 times smaller. Modifications made to the Deltascan 100 included:

1. Replacing the dual slice detector array with a single slice detector array to reduce slice thickness.

2. Installing collimating slits on the detector to both increase in-plane (X-Y) resolution and decrease slice thickness [6]. The detector collimating slits were fabricated from tungsten rods mounted on a stainless steel plate. The original slits were 12.1 mm x 3.18 mm, while the new slits are 6.86 mm x 1.73 mm. The first dimension determines slice thickness while the second determines in-plane pixel resolution.

3. Reducing the set scan circle size of 11.4 inches by adjusting the readings/element and fine spacing settings in the system software in order to increase in-plane resolution.

4. Recalibrating the scanner to fused quartz and to aluminum using the non-linearity coefficients calculations in the system software in order to reduce beam hardening artifacts.

Improvements in slice thickness and X-Y resolution were determined using appropriate inserts of a performance phantom (Computed Tomography Performance Phantom 76-410, Nuclear Associates, Carle Place, NY). The slice thickness insert consists of three 0.51 mm x 25.4 mm aluminum strips angled at 45° to the scan plane. The width of the projection of these strips in the scan plane is determined by the slice thickness. The low resolution insert of the performance phantom was used to monitor changes in resolution. This insert consists of seven sets of air-filled cavities (2.5, 2.0, 1.75, 1.5, 1.25, 1.0 and 0.75 mm) in a solid acrylic block. The spacing within each set of holes is twice the diameter of the cavities in that set, while the sets are spaced so that the centers of the cavities on the right are 5 mm apart.

Improvements in Slice Thickness

Some Deltascan 100 scanners were originally equipped with an option that consisted of a dual source-detector array. This dual array allowed two adjacent slices to be imaged during each scan. The purpose of this option was to speed up data collection. Three negative features, however, resulted from the dual slice option:

First, due to the dual source-detector geometry, slice thickness is generally greater in dual slice systems than in single slice systems. For the dual slice geometry, slice thickness was determined to vary from 8.0 mm to 8.7 mm. After the single slice system was installed, measured slice thickness decreased to 7.2 mm to 7.3 mm. This decrease improved resolution in the Z-direction (thickness) by 10-15%.

Second, an overlap can occur between slices in the dual slice system, resulting in some parts of the sample being "counted" twice in a single, two-slice data set. Measurements with the slice thickness insert showed that this overlap ranged from 0.66 mm to 1.33 mm. Because this overlap occurred in the Z direction, it affected every voxel in the image, and, in effect, resulted in data averaging between the two slices. Replacement of the dual slice system with a single slice system eliminated this problem.

Third, The Hounsfield partial volume effect is greater in dual slice systems than in single slice systems. According to Morgan [3],

> "The Hounsfield partial volume effect... is an effect described by Hounsfield which pertains only to translational-rotational systems with 180° of rotation. It is a subtle geometric effect manifested by streaks which result from the partial volume effect. The streaks result from an inconsistency between the initial and final views as a result of the partial volume effect, where dense objects (or air) only partly occupy the entire section thickness. It is complicated by the fact that the X-ray beam is divergent rather than parallel. The latter effect is particularly prominent in scanners that obtain two slices per scan, because it is necessary to angle each beam slightly with respect to its scan plane. As a result, a different fraction of the volume of an object will intercept the beam on the initial and final views. This difference is responsible for the inconsistency between initial and final views that causes the streaks. It may be suppressed by over-scanning and by reducing slice width."

Improvements in In-Plane Resolution

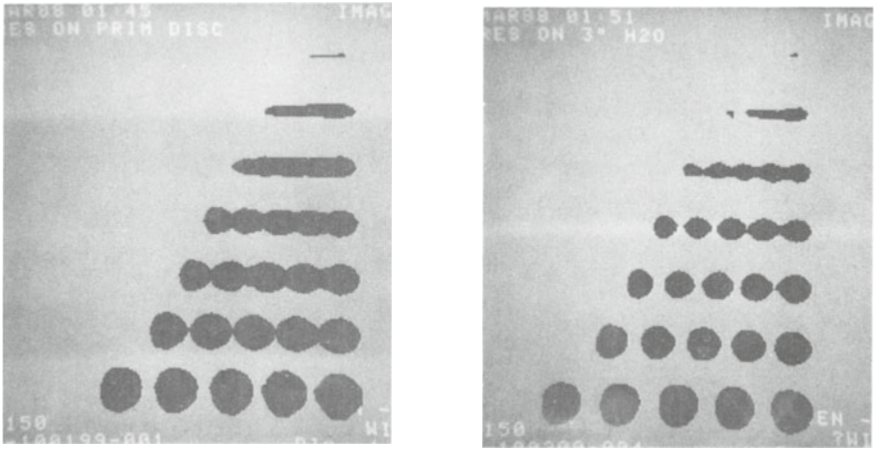
As configured for medical applications, the Deltascan 100 has a fixed scan circle size (diameter) of 11.4 in. For samples that are smaller in diameter, changing the scan circle size to more closely fit the sample results in increased in-plane resolution.

Figure 1a shows the image that is obtained when the scanner is used in the configuration established by the manufacturer. (For consistency, the gray level range of each image in Figure 1 has been set so that the center is at the lowest value found in the top row, with the window set to 0. As a result of these conditions and lack of sufficient resolution, the top row shows up only as a thin line or small circle.) Cavities above the middle row (1.5 mm) cannot be resolved. When the scanner is recalibrated to a 6.3 inch scan circle, it is now possible to resolve holes in the fifth row (1.25 mm) from the bottom (Figure 1b). Thus, reducing the scan circle in this manner reduces the pixel size by 16% in both dimensions within the scan plane. The voxel size decrease due to changing to a single slice geometry and reducing the scan circle is 40%.

Figure 1c shows the improvement in X-Y resolution when the reduced detector slit is used in combination with the smaller scan circle. Now the 1 mm holes in the sixth row from the bottom can be resolved. This represents a 33% reduction in pixel size in both the X and Y directions as compared to the original conditions. When combined with the slice thickness decreases due to both changing to a single slice and to the collimation slit, a decrease in voxel size of 72% is obtained over the original configuration of the Deltascan 100. This gain in resolution has to be traded off against an increase in image noise. For example, the root mean square deviation increased from 4.9 for an image of a water phantom imaged without slits to 7.2 for water phantom imaged with slits. The distortion in Figure 1c is probably due to misalignment of the slits.

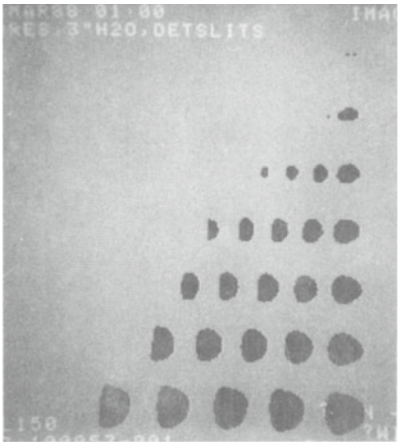
Calibration Standard Changes

Medical system software adequately corrects for beam hardening in samples with X-ray attenuating properties similar to those found in the human body. This is because medical systems are calibrated to water,



A. Original scan configuration

B. Scan circle reduced by 45%



C. Scan circle reduced by 45% plus detector slits

Figure 1. Deltascan 100 CT images of resolution phantom showing improvements in resolution due to hardware and software modifications. Diameters of circles in each image from bottom up = 2.5, 2.0, 1.75, 1.5, 1.25, 1.0, 0.75.

the major component of the human body. Most industrial samples, however, attenuate X-rays more strongly than any part of the human body, and, therefore, require additional beam hardening correction. This can be accomplished by recalibrating the system to material standards that have the same attenuating properties as the samples of interest. The Deltascan 100 was recalibrated to both fused quartz (CT = ~1400 HU) and aluminum (CT = ~2000 HU).

In the recalibration process on the Deltascan 100, a material phantom of homogeneous composition and circular cross section is substituted for the water phantom when running the program NLCALC. If the calibration is successful, the CT value of the phantom becomes zero and will not vary across the image. Subsequent samples having attenuation coefficients similar to the new phantom will not exhibit cupping and will have CT numbers close to zero.

Figure 2 compares line profiles of CT numbers across the diameters of images of a 3" diameter fused quartz phantom for a system calibrated with a water phantom and with the quartz phantom. The U-shape profile (Figure 2a) for the water calibration indicates a severe cupping problem. After recalibrating to fused quartz, the profile becomes flat, except at the edges, indicating that cupping has been mostly eliminated (Figure 2b). During the recalibration process, only 97% of the image was used to avoid including edge pixels in the calculations. This is responsible for the elevated values at the edges. The CT value of quartz is now zero with air still having a value of -1000. As shown in Figure 3, the water profile, which was orginally flat (Figure 3a), becomes concave down with the quartz calibration (Figure 3b), although not to the extent that the profile in Figure 2a is concave up. Thus, in the same way a water calibration should not be used when scanning samples with attenuations similar to quartz, a quartz calibration should not be used when scanning materials similar to water.

Figure 4 compares images of 3" diameter aluminum phantom obtained with calibration to water, quartz and aluminum. When calibrated to water, the image of this sample with an attenuation coefficient much higher than quartz shows even more severe cupping (Figure 4a). When the instrument was calibrated to quartz, a severe degradation of the image occurred (Figure 4b). Only the image obtained with a calibration to aluminum (Figure 4c) shows an almost flat profile, again with the exception of the edges. These results show that best results are achieved by using a calibration material whose linear attenuation of X-rays is closest to that of the sample.

Demonstration of Improvements Due to Scanner Modification on a Typical Sample

Figure 5 compares an image of a 3" diameter Berea sandstone at the different stages of scanner modification:

5a. Dual slice configuration.	11.4" scan circle, calibrated to water
5b. Single slice configuration.	11.4" scan circle, calibrated to water
5c. Single slice configuration.	6.3" scan circle, calibrated to water
5d. Single slice configuration.	5.8" scan circle, calibrated to quartz
5e. Single slice configuration.	5.8" scan circle, calbirated to quartz, with detector collimator slits

Image quality, as determined by the number of laminae that can be resolved, improves with each step. Also, a comparison of Figures 5c and 5d shows that changing the calibration from water to quartz significantly reduces cupping at the perimeter.

CONCLUSIONS

1. If calibrations are used, meaningful CT data on industrial samples can be obtained using medical scanners.

2. Calibrations that affect only the sample are necessary for cases in which a leased or rented scanner that cannot be modified is being used. Such calibrations include sand immersion, which improves image quality, and KI immersion, which both improves image quality and yields reproducible CT numbers.

3. More extensive calibrations affecting the scanner and scanner software can be used when scanner modification is possible. For example, the following calibrations were made to a dual slice Technicare Deltascan 100 scanner.

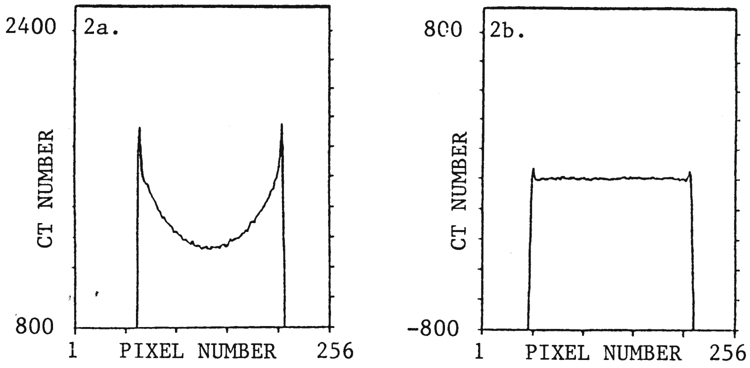


Figure 2. Line profile ot CT numbers across 3" diameter fused quartz phantom. a) calibrated to water, b) calibrated to quartz.

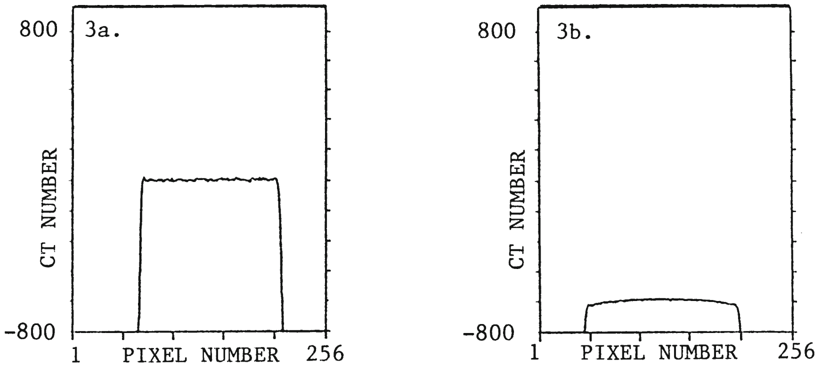


Figure 3. Line profile of CT numbers across 3" diameter water phantom. a) calibrated to water, b) calibrated to quartz.

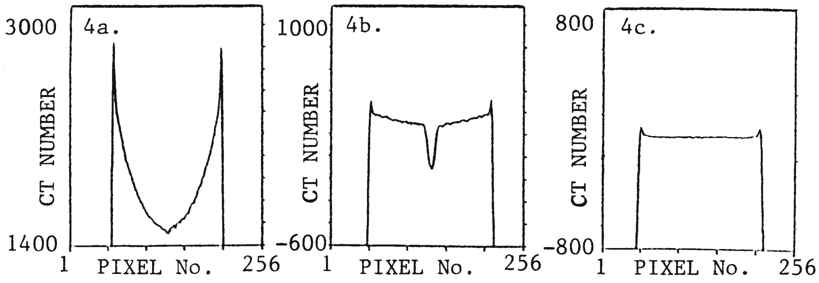


Figure 4. Line profile of CT numbers across 3" diameter aluminum phantom. a) calibrated to water, b) calibrated to quartz, c) calibrated to aluminum.

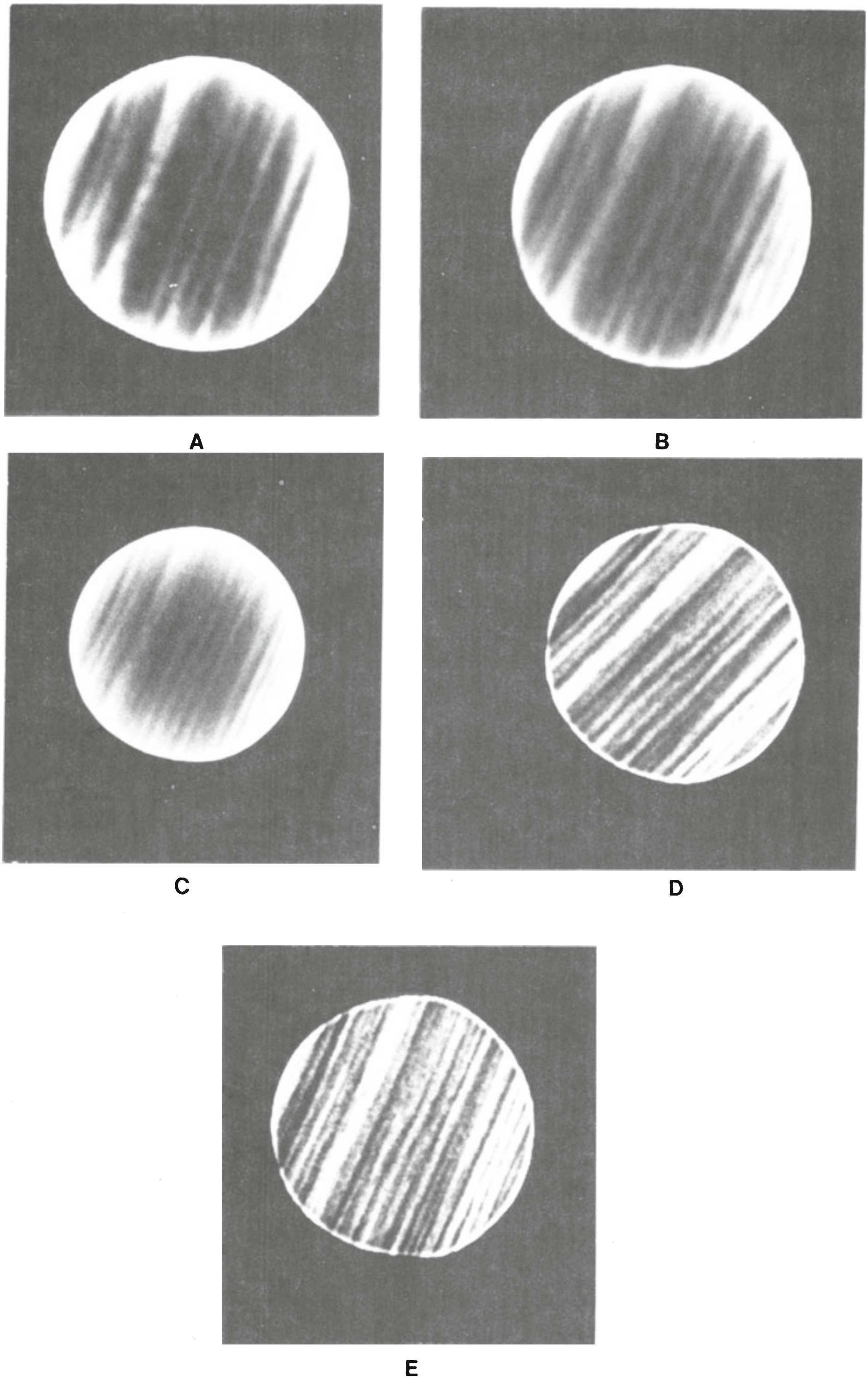


Figure 5. CT images of the same slice through a 3 inch diameter Berea sandstone at the different stages of scanner modification.

- Resolution was improved by changing from a dual slice data acquisition configuration to a single slice configuration and by modifying software parameters in order to reduce the scan circle diameter. These changes decreased voxel volume by 40%. Reducing the detector slit apertures resulted in a further decrease in voxel size. With all three changes in place, a decrease in voxel size of 72% was obtained over the original configuration of the Deltascan 100.

- The beam hardening induced cupping artifact was eliminated or significantly reduced by developing procedures to recalibrate the instrument to materials other than water. Best results are achieved by using a material whose linear attenuation of X-rays is closest to the sample, e.g. fused quartz for sandstone cores and aluminum for sintered silicon carbide.

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