A STUDY OF RECONSTRUCTION ARTIFACTS IN CONE BEAM TOMOGRAPHY USING FILTERED BACKPROJECTION AND ITERATIVE EM ALGORITHMS

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Abstract

Reconstruction artifacts in cone beam tomography are studied for filtered backprojection (Feldkamp) and iterative EM algorithms. The filtered backprojection algorithm uses a voxel-driven, interpolated backprojection to reconstruct the cone beam data; whereas, the iterative EM algorithm performs ray-driven projection and backprojection operations for each iteration. Two weighting schemes for the projection and backprojection operations in the EM algorithm are studied. One weights each voxel by the length of the ray through the voxel and the other equates the value of a voxel to the functional value of the midpoint of the line intersecting the voxel, which is obtained by interpolating between eight neighboring voxels. Cone beam reconstruction artifacts such as rings, bright vertical extremities, and slice-to-slice cross talk are not found with parallel beam fan beam geometries. Using filtered backprojection and iterative EM algorithms, the line-length weighting is susceptible to ring artifacts which are improved by using interpolated projector-backprojectors. The filtered backprojection algorithm does not produce vertical extremity artifacts seen with iterative EM algorithm, whereas cross-talk artifacts are much more severe. Data truncation artifacts are studied and some unique aspects of this problem are observed in cone beam tomography.

I. INTRODUCTION

Cone beam tomography is being investigated for various applications in medical imaging in both x-ray CT [1-3] and single photon emission computed tomography [4-7]. Several reconstruction algorithms [8-26] have been derived for various cone beam geometries that have been applied to medical applications. In general, these algorithms attempt to suppress reconstruction artifacts that result due to the limited angle sampling in cone beam tomography. However, because of the limited angle problem, cone beam tomography produces reconstruction artifacts. Here we study reconstruction artifacts for filtered backprojection [17] and iterative EM [27] algorithms. In our study, we are concerned only with artifacts that are geometrical in nature and are the result of the model used to represent the cone beam geometry. Preliminary studies of attenuation artifacts [26] and noise [28] in SPECT has been presented in previous work.

The Feldkamp algorithm [17] is used to evaluate the application of filtered backprojection algorithms to cone beam tomography. This algorithm involves an approximation in which the two-dimensional projection data are first preweighted and then filtered in only the transverse direction. The filtered data are then backprojected into the three-dimensional reconstruction volume. The backprojection is voxel-driven and requires linear interpolation of the projection samples. Generally in tomography, filtered backprojection algorithms are analytical approaches to approximating the inversion of the Radon transform and differ from iterative algorithms which attempt to solve a linear system of projection equations.

In our study, an iterative EM algorithm [27] is evaluated for cone beam tomography. The EM algorithm is designed based upon the underlying statistical properties of a Poisson distribution. In iterative methods, corrections are made to each individual voxel according to the difference between the measured projection data and the projection of the estimated reconstruction. At each iteration, one projection and one backprojection are needed to calculate a new correction. The line integral for the projection and backprojection operations are approximated by a weighted sum of the voxel intensities for all voxels that the ray passes through. Two weighting schemes for the ray-driven projector-backprojectors are investigated. One weights each voxel by the length of the ray within the voxel and the other equates the contribution of a voxel along the ray to the value of the midpoint of the line intersecting the voxel, which is interpolated between eight neighboring voxels.

The following sections give examples of ring, vertical extremity, slice-to-slice cross talk, and truncation artifacts for the Feldkamp and iterative EM algorithms. Reconstructions from simulated and phantom data are presented to illustrate the origin of these artifacts.

II. RING ARTIFACT

Two approaches to performing the backprojection operation for cone beam projections were evaluated. The first approach approximated the projection line integral by the weighted sum of each voxel intensity:

$$\int f(l) \, dl = \sum_n f_n l_n,$$

where $l_n$ is the length of the line segment within voxel $v_n$ which is along the line integral, and $f_n$ is the average of $f$ over the voxel $v_n$. The second approach uses linear interpolation to more accurately calculate the line integral of the true distribution across the voxel $v_n$. First, the length $l_n$ and the midpoint $(x_n, y_n, z_n)$ of the line segment in voxel $v_n$ are determined. Then the integers $(i_n, j_n, k_n)$ are defined such that $i_n \leq x_n \leq i_n + 1, j_n \leq y_n \leq j_n + 1, k_n \leq z_n$, and the intensity at the midpoint is approximated by interpolating linearly along the line segment between $(i_n, j_n, k_n)$ and $(i_n + 1, j_n, k_n)$.
\[ f(l) = \sum_{n, i, j, K = 0}^{1} (i_n + 1 - x_n) + l(2x_n - 1 - 2i_n) \]
\[ \times [ (j_n + 1 - y_n) + J(2y_n - 1 - 2j_n) ] \]
\[ \times [ (k_n + 1 - z_n) + K(2z_n - 1 - 2k_n) ] \]
\[ \times i_n \times f(i_n + I, j_n + J, k_n + K) . \] (2)

These two weighting schemes were incorporated into projection and backprojection operations.

A simulation was performed to evaluate the backprojection operations using the weighting in equations (1) and (2). Sixty four cone beam projections equally spaced over 360° were backprojected into a 64×64×64 array. Each projection had 64×64 bins each with a constant value of 1 and a bin dimension at the center of rotation equal to the reconstructed voxel dimension. The focal length for the cone beam geometry is equal to 112 voxel dimensions. The 64 slices of the backprojected images are shown in figures 1 and 2 using the weighting in equations (1) and (2), respectively. Ring artifacts that can clearly be seen in figure 1 are not seen in figure 2 using the interpolated backprojector.

The ring artifacts are due to unequal weighting as the ray passes from voxel to voxel, which remains constant from angle to angle. We use figure 3 which is a sagittal cut through the axis of rotation of an 8×8×8 voxel volume to illustrate the cause of these artifacts. Rays for the upper half of a cone beam geometry are shown passing through the sagittal plane. This vertical cut through the cone beam geometry looks like a fan beam geometry at two projection locations 180° apart.

First let us look at why there are no ring artifacts in slice 3 in figure 1. If we consider the first row above the central horizontal line in figure 3, we see one ray from the focal point on the left and one from the focal point on the right travelling through this row. Within each voxel, the segment length intersecting each voxel by both rays are identical. Therefore there will be uniform weighting throughout this particular slice for each projection angle and no rings will appear.

Next, if we consider the second row above the central horizontal line in figure 3, we can explain the cause of the ring artifacts observed in slice 31 of figure 1. The second voxel from the left and right has contribution from three rays and is weighted more than the other voxels on the same row. Therefore, the backprojection will produce a bright ring through those voxels in the second slice that are at the same radius from the axis of rotation as these two voxels. In general, we see that across the row each voxel is unequally weighted. Since the voxel intensity in the backprojection is the sum of line segments, the backprojection of the cone beam projections will give bright and dark rings across the slice.

III. VERTICAL EXTREMITY ARTIFACT

We found in simulations with an iterative EM algorithm that vertical extremity artifacts were observed in regions where the contrast changed sharply in the direction parallel to the axis of rotation. To illustrate these artifacts, a phantom was reconstructed from 64 projections equally spaced over 360° into a 64×64×64 voxel array using 15 iterations of the iterative EM.
algorithm [27]. The sampling dimensions at the center of rotation were equal to the reconstructed voxel dimension. The focal length was equal to 112 voxel dimensions. A projection and backprojection operation which used the interpolated weighting given in equation (1) was accomplished at each iteration. The projection data were generated using a cone beam phantom generator that analytically calculated the line integral through the phantom which was composed of ellipses of different intensities. No noise was added to the projections; however, in one simulation, a lowpass filter was applied to the projection data along the direction parallel to the axis of rotation.

Figure 4 shows a series of sagittal slices through the three-dimensional reconstructed image. One observes that a few voxels are very bright at the top of the phantom, whereas the edge intensity should be uniform. Figure 5 shows the results reconstructed from the projections filtered in the direction parallel to the axis of rotation. Compared with figure 4, the internal objects are brighter due to the reduced amplitude at the top of the phantom. Therefore, the application of the lowpass filter along the direction which is parallel to the axis of rotation reduces the vertical extremity artifacts.

Like ring artifacts, the vertical extremity artifacts are only found in cone beam geometry. Unlike ring artifacts, the vertical extremity artifacts are not the result of the line-length projector-backprojector, but are the result of the underlying principles of the iterative algorithm. In order to explain how the vertical extremity artifacts occur, attention is drawn to figure 6 where we use, as in figure 3, a sagittal cut through the axis of rotation of an 8x8x8 voxel volume. We assume that the object is a solid sphere of uniform intensity, which in the sagittal slice appears as a circular disk. To make it easier for discussion, the small grid boxes are labeled as matrix entries. For example, the voxel at the upper right corner is labeled $v_{18}$; the voxel at the lower left corner is labeled $v_{8}$; and so forth. Along the rotation axis, $p_{1}, p_{2}, p_{3}, ..., p_{8}$ are the projection data.

Iterative algorithms update the voxel intensity values such that the projections of the reconstructed image tend toward the actual projection data. When the algorithm converges, the difference between the actual data and the reprojected data of the reconstruction should be zero for an underdetermined data set that is consistent. For our underdetermined system illustrated in figure 6, we assume that the algorithm will tend to solutions that satisfy the equations. If $p_{z} = 0$, then $f_{13}, f_{14}, f_{15}, f_{16}, f_{21}, f_{22}, f_{23}, f_{26}, f_{27}$, and $f_{28}$ will be zero. Also, $f_{11}, f_{12}, f_{17}, f_{18}, f_{31}, f_{38}$ are forced to be zero by projection equations perpendicular to this vertical plane. For $p_{2} \neq 0$, the line length model requires

$$
p_{2} = [l_{31} f_{31} + l_{32} f_{32} + l_{22} f_{22} + l_{23} f_{23} + l_{24} f_{24} +
+ l_{25} f_{25} + l_{26} f_{26} + l_{27} f_{27} + l_{17} f_{17} + l_{18} f_{18}]
+ [l_{38} f_{38} + l_{37} f_{37} + l_{27} f_{27} + l_{26} f_{26} + l_{25} f_{25} +
+ l_{24} f_{24} + l_{23} f_{23} + l_{22} f_{22} + l_{12} f_{12} + l_{11} f_{11}]. \quad (3)
$$

Due to the reason mentioned above, $f_{22}, f_{23}, f_{26}$ and $f_{27}$ are forced to be zero. Hence, equation (3) will assign greater values to $v_{24}, v_{25}, v_{32}$ and $v_{37}$ than their actual values according to

$$
p_{2} = 2[l_{24} f_{24} + l_{25} f_{25}] + l_{32} f_{32} + l_{37} f_{37}. \quad (4)
$$

Because those top values are greater than they should be, a bright artifact at the top results. We again point out that this vertical extremity artifact is inherent for cone beam geometry, and is the result of quantization.

The vertical extremity artifacts show at those regions of high contrast where the contrast gradient changes sharply parallel to the axis of rotation; for example, near an edge for example. For cone beam geometry, the lines of projection remain tangent to the surfaces of discontinuity of the original density distribution for all projection angles. Full angular sampling of the projection data is not possible. For parallel beam and fan beam cases, this "bright edge" artifact is not observed because a point of discontinuity does not remain tangent to a projection line as the collimator (or equivalently, the object) rotates. Also, the artifacts will be more severe further away from the horizontal central plane. To see this, let $p_{3} = 0$ and $p_{4} \neq 0$ in figure 6. The

![Figure 3. A sagittal cut of a reconstruction volume.](image-url)
4 was reconstructed into a 32×32 and 64×64 array from 64 projections sampled over 360° using only the iterative EM reconstruction algorithm. The dimensions of the cone beam geometry and voxel dimensions were the same as in the type one simulations. Simulations differ in that the projection data were not truncated but instead a smaller region of the image (32×32 inner region) was reconstructed.

Simulations showing type two artifacts are shown in figure 17. The image in figure 17(a) is a reconstruction of a 32×32 subregion of that 64×64 reconstruction in figure 17(b). Both results were obtained using the iterative EM algorithm. Type two truncation artifacts are not observed using the Feldkamp algorithm. It is obvious that these types of reconstructions can be overcome by reconstructing into a larger array. However, for cone beam geometry, many times the reconstruction volume is reduced in order to minimize the computational demands.

Type one truncation artifacts are the result of the projection of the object extending outside the field of view both in the transaxial direction and parallel to the axis of rotation. The detector sees only a subregion of the object and the projection profile abruptly goes to zero near the edge of the field of view. In the filtered backprojection (Feldkamp) algorithm, the highpass filter (or convolution operator) enhances the edges of the projection profile and a circle-like bright truncation artifact shows in the reconstructed transaxial image (see figure 11(b)). Since no filtering is performed in the axial direction, no truncation artifacts appear parallel to the axis of rotation (see figure 13). A smoothing filter can reduce the ring-type artifact in the transaxial planes. However, a better approach is to extrapolate the projection data so that they approximate the projections that would be obtained if they could be fully sampled [30].

In the iterative EM algorithm, no highpass filter is applied so the truncation artifacts appear as a dark ring instead of a bright ring in the transaxial slices (see figure 11(a)). In the z direction (parallel to the axis of rotation), there is truncation of the object in figure 15, where the field of view cuts into the object at the bottom of the object. These result in the bright triangular artifacts shown in the sagittal views. These artifacts are not seen with the Feldkamp algorithm in figure 13 and as we discussed for the vertical extremity artifact, occur because the EM algorithm is attempting to solve an underdetermined system of equations. For the cone beam geometry, the iterative algorithm tends to assign larger values to regions which are seen from all projection angles than those that are not. Sometimes the artifact values are so large that the effective dynamic range is reduced and image detail is lost. When we use cone beam iterative algorithms, the data at the top and bottom of the projection planes should be very small, or else very bright truncation artifacts will result. In these cases where the projection data at the two ends are large, the projection data can be extended vertically.

The second type of truncation artifact shows up whenever the image volume is smaller than the original object seen by the collimator (see figure 10). The reconstruction volume is not large enough to reconstruct the entire object even though the projections are measured by the camera. The parts of the object missed by the projector-backprojector cause the edge of the reconstruction volume to be much brighter than they should be in order to match the acquired projection data. It is very easy to remove this type of truncation artifact by making the reconstruction volume bigger. The second type of truncation artifact is not found with filtered backprojection algorithms because reconstruction is accomplished point-by-point as an approximation to a continuous reconstruction algorithm. Therefore, when we use filtered backprojection methods, the reconstruction volume can be very small, only large enough to contain the region of interest. On the other hand, for iterative
algorithms, the reconstruction volume should be large enough to include everything which is seen by the field of view.

VI. DISCUSSION

This paper studied the potential reconstruction artifacts observed with cone beam tomography and analyzed the origin of the artifacts as a function of the filtered backprojection and iterative EM algorithms. The ring, vertical extremity, and cross talk artifacts which we demonstrated are unique to cone beam tomography. On the other hand, truncation artifacts are found with all types of reconstruction geometries, however, some aspects of the problem such as truncation in the axial direction only occur with iterative reconstruction of cone beam
projections. We demonstrated that reconstruction artifacts are a function of the algorithm and the weighting used in projection and backprojection operations.

Ring artifacts are directly related to the weighting scheme used in the projection and backprojection operations. A voxel driven backprojector that bilinearly interpolates either the projections or filtered projections in the Feldkamp algorithm, does not produce ring artifacts in the backprojected or reconstructed images. However, the line-length weighting used with ray driven projector-backprojectors causes significant ring artifacts with cone beam tomography no matter whether filtered backprojection or iterative EM reconstruction algorithms are used. The cause of the artifacts are very much akin to the cause of uniformity artifacts observed in SPECT imaging [31]. We demonstrated that by using an interpolation method, these artifacts can be removed only in the regions where each voxel is sampled at least by one projection ray. The development of an artifact-free projector-backprojector is especially important in being able to model photon attenuation in SPECT imaging [26].

Unlike ring artifacts, vertical extremity artifacts are directly a function of the reconstruction algorithm. These artifacts are directly the result of the underlying principles of the reconstruction algorithm. The vertical extremity artifact is primarily due to a partial volume effect where the EM algorithm is attempting to obtain a minimum norm solution to an underdetermined system of equations so that at boundary voxels where two or more rays passing through the voxel have projection samples of zero and nonzero values. In solving the underdetermined system of equations, one voxel is set to zero while neighboring voxels are over estimated producing a bright edge discontinuity instead of a smooth transition. The filtered backprojection algorithm does not produce these artifacts because the point response of the algorithm tends to smooth reconstructed values between neighboring voxels. The vertical extremity artifacts which are primarily seen in the upper and lower ends of the reconstructed image in the axial direction, can be reduced by lowpass pre-filtering the projection data along the direction of the rotation axis. For patient data, we have found that the point spread function of the SPECT system will filter the projection data and these artifacts will not be observed as readily.

The filtered backprojection algorithm helps to reduce the vertical extremity artifact, whereas it significantly magnifies the slice-to-slice cross-talk. The iterative EM algorithm produces less cross-talk between slices than does the Feldkamp algorithm. The slice-to-slice cross-talk artifact is inherent to cone beam geometry and is the result of incomplete projection sampling.

Two types of truncation artifacts were investigated and some unique aspects of this problem are observed in cone beam tomography. Type one artifacts are the result of the object extending outside the field of view. For cone beam geometry, this can occur both transaxially and in the axial direction. The impetus for using cone beam geometry is to magnify small organs such as the heart in order to improve the sensitivity and resolution. In so doing, a portion of the pharmaceutical distribution will extend outside the field of view. This truncation causes reconstructed ring artifacts but by utilizing data extension methods, the artifacts can be significantly reduced [30]. The type two truncation artifact occurs only with iterative EM algorithms and is the result of attempting to reconstruct a reduced volume of interest from that measured. It may seem trivial to correct this by just reconstructing a larger volume. However, this can be a critical problem with iterative cone beam algorithms when it becomes computationally impractical from a time perspective, and thus large reconstruction volumes are undesirable.

The results presented here are important in interpreting clinical results. Preliminary clinical studies of cone beam tomography in cardiac imaging show promising results with good image quality and only minimal image distortions [32]. These results have important implication for SPECT imaging of
projection sample \( p_3 \) does not have any effect on the voxels in the slice below it. This will not be the case as you move further from the central slice where rays begin to cross transaxial slices. Even the linear interpolation (equation (2)) in the projector-backprojector will not help in this situation. For example, \( f_{33} \) will always be set to zero no matter what kind of line integral approximation we choose. However, a lowpass filter applied to the cone beam projection data along the direction parallel with the axis of rotation reduces these artifacts.

We assume a strong consistency in the projection equations in our analysis. The analysis remains true when the equations are not quite consistent, since the iterative algorithms attempt to match these equations in maximizing likelihood.

**IV. SLICE-TO-SLICE CROSS TALK**

Cross talk from transaxial slice to transaxial slice is another artifact we have observed in cone beam tomography which is not observed in fan beam or parallel beam tomography because the reconstructions are performed slice by slice. To study this effect, we used a phantom consisting of 7 parallel disks of identical uniform intensity equally spaced at 10 voxels apart parallel to the rotation axis [29]. Each disk has a diameter of 64 voxels and a thickness of 2 voxels. Both the iterative EM algorithm and the Feldkamp algorithm were used to reconstruct the simulated data. A three-dimensional image was reconstructed from 64 projections equally sampled over 360° into a 64×64×64 voxel array. The sampling dimension at the center of rotation, equals the reconstructed voxel dimension, and the focal length equals 112 of these voxel units. For the EM algorithm, 15 iterations were performed and the interpolated weighting in equation (2) was used in the projection and backprojection operations.

Figure 7(a) shows a sagittal cut through the axis of rotation of the three-dimensional reconstruction using the iterative EM algorithm. One observes that the cross talk artifact becomes more severe as the distance from the horizontal central plane increases. Cross talk artifacts arise from not adequately sampling the voxels with projection rays from sufficient angular samples. The cross talk artifacts from transverse slice to transverse slice become worse as you move away from the central plane because there are fewer rays that sample transversely. Whereas, on the central plane no cross talk artifacts are found because of complete projection sampling.

Figure 7(b) shows the same sagittal cut as in figure 7(a) of the three-dimensional reconstruction using the Feldkamp algorithm. In comparing figures 7(a) and 7(b), it is obvious that the cross talk artifact is more severe with the Feldkamp algorithm than with the iterative EM algorithm.
Cone beam cross talk artifacts are caused by incomplete projection data. For the filtered backprojection algorithm, the incomplete sampling causes significant smearing from slice to slice.

For the iterative EM algorithm, the incomplete sampling introduces an underdetermined system of equations, which if consistent, has an infinite number of solutions. Suppose we have only one projection shown in figure 8 that gives the following linear equation with two unknowns:

$$x_1 + x_2 = 4$$  \hspace{1cm} (5)

There are an infinite number of solutions, such as $x_1 = 1, x_2 = 3$, $x_1 = 2, x_2 = 2$, etc. Suppose the true value for $x_1$ is 0 and for $x_2$ is 4. Because of the incomplete nature of the data, the algorithm will converge to $x_1 = 2$ and $x_2 = 2$ which is a minimum norm solution. Thus, this smears the reconstruction voxels. The EM does a better job of forcing solutions that satisfy the other projections than does the filtered backprojection algorithm, and thus reduces the smearing from slice to slice.

V. TRUNCATION ARTIFACTS

There are two types of truncation artifacts encountered in reconstructing parallel, fan beam, and cone beam data. Type one truncation artifacts are the result of data acquisition procedures using a short focal length and a small diameter imaging detector causing the projection of the object to extend outside the field of view (figure 9). Type two truncation artifacts result from reconstructing an image volume smaller than the original object even though complete projection data is measured by the detector (figure 10). Type two truncation artifacts only occur with iterative reconstruction algorithms. In this section we illustrate type one and type two truncation artifacts with filtered backprojection and iterative EM algorithms.

A simulation was performed to illustrate type one truncation artifacts that can occur in the transaxial plane. The central slice of the phantom in figure 4 was reconstructed into a 64x64 array from 64 projections sampled over 360° using the Feldkamp and iterative EM reconstruction algorithms. The sampling dimensions at the center of rotation equal the reconstructed voxel dimension. The focal length was equal to 112 voxel dimension. The inter 50 projection samples in each view were preserved and the outer 7 projection samples of the simulated data were set to zero. In the EM algorithm, the projections beyond the truncation edge were not included in the projection equations. In other words, it was assumed that no data existed for these projections. Therefore, the reconstructed voxel values were not determined based upon these projection samples being zero. A completely different result would have been obtained if reconstructions were obtained assuming the data was zero beyond the truncation edge.

Simulations showing type one artifacts in the transaxial plane are shown in figure 11. The results of the iterative EM and Feldkamp algorithms are shown in figures 11(a) and (b), respectively. One can compare them with a reconstruction without truncation (see figure 17(b)). For the iterative EM algorithm the artifact appears as a dark outer ring, whereas for the Feldkamp algorithm, the artifact appears as a bright ring. For non-circular camera orbits, we have observed that the artifacts are not symmetric. The type one truncation artifact obtained with the iterative EM algorithm is not as severe as that obtained with the Feldkamp algorithm.

To illustrate the truncation artifacts that occur in the direction parallel to the axis of rotation, data from a Carlson phantom (see figure 16) was collected using a Picker SX-300 SPECT system with a 50 cm focal length cone beam collimator. The reconstruction of 128 projections equally sampled over 360° into a 64x64x64 voxel volume (4 mm voxels) was obtained using 15 iterations of the EM algorithm and compared with that obtained using the Feldkamp algorithm. The interpolated weighting in equation (2) was used by the iterative EM algorithm in the projection and backprojection operations.

Reconstructions of the Carlson phantom are shown in figures 12 - 15 to illustrate type one truncation artifacts occurring parallel to the axis of rotation. Figure 12 shows the reconstructed transaxial slices using the Feldkamp algorithm. Figure 13 shows the sagittal cuts of the reconstructed image shown in figure 12. Figure 14 shows the reconstructed transaxial slices using the iterative EM algorithm. Type one truncation artifacts can be seen both in transaxial slices (figure 14) and in sagittal cuts of the reconstructed image (figure 15) which are not observed with the filtered backprojection algorithm (Feldkamp). In the sagittal cuts the truncation artifacts are seen at the top of the phantom in figure 15 as a bright triangular artifact.

Another simulation was performed to illustrate type two truncation artifacts. We again used the same phantom used for the type one artifacts. The central slice of the phantom in figure
the heart in terms of providing better detectability of myocardial infarcts and better diagnosis of ischemic heart disease. Future work is still needed to better understand the effects of reconstructed geometric distortions and noise texture [28] on lesion detection.

ACKNOWLEDGMENTS

The research work presented in this manuscript was partially supported by NIH Grant No. RO1 HL 39792 and the Whitaker Foundation. We want to thank Paul Christian for supplying the phantom data.

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