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INTEGRATED CT/BRONCHOSCOPY IN THE CENTRAL AIRWAYS: PRELIMINARY RESULTS

Melissa J. Suter, Ph.D.⁴, Joseph M. Reinhardt, Ph.D.³, and Geoffrey McLennan, MD, Ph.D.^{1,2,3}

¹ Department of Internal Medicine, University of Iowa, Iowa City, IA

² Department of Radiology, University of Iowa, Iowa City, IA

³ Department of Biomedical Engineering, University of Iowa, Iowa City, IA

⁴ Harvard Medical School and Wellman Center for Photomedicine, Massachusetts General Hospital, Boston, MA, USA

Abstract

Rationale and Objectives—Many imaging modalities and methodologies exist for evaluating the pulmonary airways. Individually, each modality provides insight to the state of the airways however, alone they do not necessary provide a comprehensive description. The goal of this paper is to integrate complementary medical imaging datasets to form a synergistic description of the airways.

Materials and Methods—Two digital bronchoscopy techniques were used to evaluate the pulmonary mucosa. A digital color bronchoscopy system was used to detect mucosal color alterations, and a fluorescence detection system was used to assess the microvasculature of the bronchial mucosa. Study participants were also imaged with a multi-detector row computed tomography (MDCT) scanner. Virtual bronchoscopy and image registration techniques were exploited to combine 3D surface renderings, extracted from the MDCT data, together with the 2D digital bronchoscopy images. Validation of the fusion process was performed on a rubber phantom of an adult airway with 4 embedded metal beads.

Results—The fusion of the MDCT extracted airway tree and the digital bronchoscopy datasets were presented for 3 study participants. In addition, the detected accuracy of the registration method to reliably align the MDCT and bronchoscopy image datasets was determined to be 1.98 mm in the phantom airway model.

Conclusion—We have demonstrated that merging of three distinct digital datasets to provide a single synergistic description of the airways is possible. This is a pilot project in the field of eidomics, the process of combining digital image datasets and image based processes together. We anticipate that in the future eidomics will provide a universal and predictive imaging language that will change health care delivery.

Corresponding Author and Requests for Reprints: Geoffrey McLennan, M.D., Ph.D., Professor of Internal Medicine, Biomedical Engineering and Radiology, The University of Iowa, Roy J. and Lucille A., Carver College of Medicine, 200 Hawkins Drive, C325-GH, Iowa City, IA 52242, P (319) 356-3603, F (319) 353-6406, E-mail: Geoffrey-mclennan@uiowa.edu.

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Eidomics; digital bronchoscopy; computed tomography; virtual bronchoscopy; fusion of 2D and 3D medical image datasets

INTRODUCTION

Pulmonary airway diseases such as chronic obstructive pulmonary disease (COPD), including emphysema and chronic bronchitis, and asthma are the fourth leading cause of death in the world (1). Increased mucus production and airway inflammation are generally associated with COPD and asthma, and persistence of this chronic irritation can in many cases lead to permanent damage. Lung cancer is the leading cause of cancer related death in the United States, accounting for 29% of all cancer deaths (2). Despite recent efforts to reduce the mortality associated with this disease, patient prognosis remains poor, with the current 5-year survival rate under 15% (2). The prevalence and high mortality rate associated with lung cancer, and other pulmonary airway diseases, gives impetus to the need for new highly accurate and sensitive screening tools with the objective of early detection and diagnosis. As a result, many imaging modalities currently exist including chest x-ray (3,4), computed tomography (5,6) (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and white light bronchoscopy. In addition, many more new novel imaging techniques, such as optical coherence tomography (7), confocal microscopy (8), digital color bronchoscopy (9), fluorescence bronchoscopy (10,11), and autofluorescence bronchoscopy (12,13), are being developed. These existing and emerging technologies may provide invaluable insights to one or more facets of the disease assault on the affected tissue, however in many cases do not comprehensively reveal all of the structural and functional changes that occur.

The purpose of this research is to extract and utilize the informative aspects from 2D and 3D imaging modalities and combine these to form a comprehensive synergistic dataset. Digital image datasets are full of complex information, and due to the ever increasing number of imaging modalities available, physicians must often rely on computer aided methods to interrogate and possibly interpret these large image sets. Many times physicians do not have the opportunity to look at the images but rely instead on written reports. As images convey an extraordinary amount of information, subtleties visible only to the master clinician may often be missed as a result. It is clear that the investigating physician must view the image data. *Eidomics* ('*eidos*' Gk for image structure, and '*omics*' Eng for biology) is the process of combining digital image datasets with informative image-based manipulations, which may be powered by artificial intelligence, and displaying the conglomerate of information rich results with superior end-user visualization tools. Such visualization tools may include dynamic interactive simulations or animations. The eidomic model may additionally incorporate patient information, or a priori information derived from image databases, to better predict disease behavior.

In this paper we will present a new method for combining 2D images obtained from both digital white light bronchoscopy and fluorescence bronchoscopy, together with information extracted from multi-detector row computed tomography (MDCT). The fusion process occurs through 1) MDCT virtual bronchoscopy generation (14), 2) distortion correction of the digital bronchoscopy images (15), 3) registration of the virtual bronchoscopy with the distortion corrected digital bronchoscopy images (14,16,17), 4) determining depth values and corresponding real world coordinates, 5) intensity correction of the color bronchoscope images and subsequent display. This fusion of MDCT and digital bronchoscopy datasets is a pilot project in the field of eidomics. The amalgamation of 3D structural information from MDCT

and 2D digital bronchoscopy images may result in a more comprehensive and understandable multi-modal description of the pulmonary airways than was previously obtainable.

MATERIALS AND METHODS

Attempts in medical imaging to apply texture maps to 3D structures have typically been performed through the manual selection of image features in each of the complementing imaging modalities. The 2D texture maps are consequently warped or wrapped onto the 3D structural surface based on the chosen landmark locations. Although this form of texture mapping does produce realistic images the process has many inherent limitations including the speed and accuracy of the manual landmark selection, the limited number of landmarks selected, and an inability to account for non-uniform illumination effects that may be detected in the texture image. Alternative shape from shading algorithms can be used to generate 3D structures from the 2D bronchoscopy images (18,19), however this process is highly susceptible to modeling of the illumination source, and the proximity of the source to the bronchial wall. As a result the 3D representations often do not accurately describe the true 3D geometry. Here we describe a new automated approach to texture mapping of the bronchial mucosa by utilizing virtual bronchoscopy, including multi-modal image registration results, by applying color intensity correction to the texture maps, and by performing endoscope position based texture merging. A block diagram representing the major processing steps is provided in Figure 1. We will provide a brief description of the steps involved in generating and registering the digital virtual and actual bronchoscopy image sets, and will then focus on the actual processing steps required to merge the datasets once the initial registration is made.

Airway Imaging Modalities

MDCT—External imaging modalities, such as MDCT, have been shown to provide increasingly valuable insight to the structural, and in some cases functional, changes occurring as a result of bronchial diseases. This is especially evident in the peripheral lung where assessment with traditional methods, such as bronchoscopy, are not possible. The structural analysis associated with 3D volumetric MDCT datasets may include the assessment of airway tree diameters, surface topography, and airway wall thickening (20,21). Presently research in functional MDCT imaging, which is often not recognized as an aspect of MDCT imaging, includes regional ventilation and perfusion studies, and the study of regional pulmonary vascular transport characteristics (22,23). MDCT benefits further extend to the planning of airway stenting procedures, such as stent sizing, the longitudinal examination of individual subjects, and to surgical planning. Although the use of volumetric MDCT imaging in the detection and diagnosis of respiratory disease has many advantages as previously mentioned, MDCT images lack important information regarding airway mucosal color that is attainable with bronchoscopy procedures.

Color bronchoscopy—The development of pulmonary airway disease produces observable color changes in the bronchial mucosa. Assessment of the airways through traditional bronchoscopy is relatively non-invasive, and provides a visual link to the mucosal topography and color, however, the subtle color variations that indicate early disease development may often be missed as a result of this highly subjective assessment especially by inexperienced bronchoscopists.

We have developed a digital color bronchoscopy acquisition and analysis system to accurately detect bronchial mucosal color alterations that occur as a consequence of pulmonary airway disease (9). The developed imaging system was designed to operate during a standard bronchoscopy procedure, to detect airway mucosal color abnormalities and to provide real-time feedback to the physician. We have previously demonstrated that this system can

accurately distinguish between healthy mucosa, and mucosa with known pathology including carcinomas, granulation tissue, papillomatosis and stenosis (9). In this study we utilized the bronchoscopy system to acquire color images of the pulmonary airways to merge with the MDCT segmented airway tree.

Fluorescence bronchoscopy—Alterations to airway mucosal microvasculature frequently occur in response to the development of pulmonary airway diseases such as lung cancer, inflammatory bronchitis or cystic fibrosis. As such, investigating the sub-epithelial vasculature is crucial to enhancing our understanding of airway responses to changing mucosa structure and composition (24). To date most investigators have focused on the larger vessels of the pulmonary circulation due to the difficulty associated with measuring blood flow in the microcirculatory system.

Fluorescein angiography is commonly used to qualitatively evaluate the circulation of the retina in order to detect and diagnose diseases including diabetes (25,26). In addition to the use of fluorescein in ophthalmology applications we believe that fluorescein has a potential use in determining changes in airway mucosa vasculature. By monitoring the fluorescent emission in the airway tree we hypothesize that regions of airway mucosa corresponding to high or low intensity fluorescent emission will correlate with high or low tissue vascularity.

We have previously developed a fiber optic bronchoscopy based fluorescence detection system and have used this system to observe the microvasculature of the rabbit trachea (10,11). A bolus of fluorescein was administered intravenously and the transient fluorescence response was observed in regions of mucosa previously exposed to vasodilators and vasoconstrictors. Based on the success of the rabbit study, we are currently conducting a limited pilot study assessing the microvasculature of the bronchial mucosa in both healthy patients and patients with known pulmonary pathology. Although to date no conclusive data has been obtained, we hypothesize that observing the mucosal fluorescein emission in both healthy and diseased airways may provide additional insight to the possible microvasculature response to airway inflammation. In this study fluorescein was administered to one of the study participants and the transient fluorescence emission was observed. The collected images were consequently merged with the MDCT segmented airway tree.

The Fusion Process

1. Virtual Bronchoscopy Generation—The development and clinical use of virtual bronchoscopy software has increased in recent years due in part to the advancements in MDCT scanners. A virtual bronchoscopy is a computer-generated visualization of a traditional bronchoscopy procedure and provides a simulated view of a bronchoscope traversing the pulmonary airways (14). The structure of the pulmonary airways is extracted from MDCT volumetric data through automated airway tree segmentation. Segmentation of the airway is based on a region growing technique. The user selects a seed voxel in the trachea as an initialization parameter. The neighboring voxels of the seed point are then assessed to determine if they are part of the airway or of the surrounding wall or parenchyma tissue. This region growing voxel selection is an iterative process. Following the segmentation of the airway, a surface mesh is generated to produce the surface skeleton. The surface is subsequently rendered, assuming Lambertian surface properties and a diffuse shading model, and is visualized by defining the camera (or bronchoscope) position and a perspective projection camera model, to generate the virtual bronchoscope view. Virtual lighting and shading is applied from the camera position to the rendered surface to simulate the bronchoscope light source and thus to produce realistic 3D views. By altering the 3D axes position of the virtual bronchoscope it is possible to observe different virtual views and hence traverse the virtual airway environment.

2. Distortion correction of digital bronchoscope images—Generally, endoscopes used in current clinical practice are designed to include fish-eye lenses that induce barrel distortion in the resulting image output. The reason for the inclusion of these lenses is to increase the field of view of the bronchoscope providing the physician with a greater view of the airway wall. As a result of the fish-eye lens, the interpretation of the image scene is compromised. When registering virtual and digital bronchoscope images it is required that either the digital bronchoscope view be distortion corrected, or the identical barrel distortion be applied to the virtual bronchoscope view. In this paper our final goal is to present the digital bronchoscope data in the 3D space and therefore we chose to correct the distortion on the digital bronchoscope images. Many algorithms exist for lens distortion correction. One such algorithm was introduced by Asari *et al.* in 1999 (27) where distortion parameters were calculated to align a rectangular grid of dots onto a set of adjacent lines. This method had the advantage that the calibration set-up did not require the bronchoscope tip to be exactly perpendicular to the calibration grid, however, as a result would produce a trapezoid shape result where the calibration lines did not map parallel to one another. Zhang *et al.* in 2000 (15–17) modified Azari's approach to require that the mapping of both the horizontal and vertical lines be parallel to one another. This approach, used in this paper, does improve the selection of the optimal distortion center and overall solution but has the disadvantage that precise alignment of the calibration setup is required. The calibration parameters only need to be calculated once for each bronchoscope used. Figure 2 depicts results from the endoscope distortion correction algorithm.

3. Virtual and digital bronchoscopy registration—Once the virtual bronchoscopy views have been generated and the digital bronchoscopy images have been distortion corrected, the imaging modalities can be registered. An initial registration of the virtual and digital bronchoscope images is performed in an easy to locate region of the airways such as the trachea, and then a matching algorithm is employed to track the bronchoscope's progress throughout the airways and display the corresponding virtual bronchoscope view (17). By utilizing this matching property, the bronchoscope location within the airway tree can be determined and the endoluminal dimensions calculated.

In 1997 Viola and Wells (28,29) presented a method of correlating images and models through intensity based maximization of mutual information rather than previous feature based approaches. This registration method assumes that although the differing imaging modalities are likely to have different pixel intensities for corresponding image pairs, the image geometry should appear similar. An example of this is a gray scale image of an apple and its inverse. Although the apple may appear black on a white background in one image, and white on a black background in another, they are essentially the same image. The mutual information $I(\cdot)$ between the two images, the reference image u and the image to be registered v , can be described in terms of entropy where T is the transformation, x is the coordinates of the image and $h(\cdot)$ is the entropy of a random variable (28,29).

$$I(u(x), v(T(x))) \equiv h(u(x)) + h(v(T(x))) - h(u(x), v(T(x))) \quad [1]$$

The first term on the right side of the above equation represent the entropy of the reference image (digital bronchoscope image) and thus is fixed, the second term is the entropy of the image to be registered (the virtual bronchoscope image), and the third term is the joint entropy of the two. To find the best alignment of the two images we need to find T that maximizes $I(\cdot)$. This will occur when the second term is at a maximum to ensure that the virtual image has a variety of grayscale values, and the third term a minimum with consistent grouping between the two images. The registration method used, although based on this approach was modified

by adding weighting factors to favor the darker image intensities, such as bifurcation regions of the airways(16). The reasoning behind the intensity weighting in the entropy calculations is that the darker image regions generally have less noise than the lighter regions. The light regions often exhibit image singularities or noise in the digital color bronchoscope images. This noise may be a result of such things as bright illumination source reflections from surface fluid in the airways, or image blurring from rapid bronchoscope or airway movement. Alternatively, the darker image regions are generally indicative of major airway wall structure such as direction or significant surface landmarks. The determined weights are applied to the entropy terms used in the mutual information calculation. The digital color bronchoscopy images are converted to gray scale intensity images for the registration process. Gray scale values are determined by converting the red, green, blue (RGB) images to the hue, saturation, intensity (HSI) color space and using the I values only.

To find the position of the virtual bronchoscope image that maximizes the mutual information with the digital bronchoscope image, optimization search techniques are applied. The viewpoint is defined with six degrees of freedom, 3 of translation and 3 of rotation. The optimization method used is the Nelder-Mead simplex approach (30).

4. Determining range values and real world coordinates—When virtual bronchoscopy software generates the virtual view, the rendered result is displayed in a 2D format. The range or depth information for each pixel in the 2D image, at the current viewpoint, is stored in a buffer. By accessing these range values it is possible to associate a depth value to each of the pixels in the 2D virtual image and, owing to the registration of the virtual image with the digital bronchoscopy image, we are consequently able to associate the depth values to the digital bronchoscopy image. The resulting depth map with texture RGB values can then be projected into 3D real world coordinates by scaling the result by the MDCT image spacing, to obtain values in millimeters.

As previously mentioned, to generate a virtual bronchoscope view a perspective projection model (pinhole camera) is used. The transformation of a point, $p(x, y, z)$ to its corresponding position in a perspective projection model, $p'(x', y', z')$ can be defined by the following transformation equation.

$$p' = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{d} & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} x' \\ y' \\ z' \\ \frac{z'}{d} \end{pmatrix} \quad [2]$$

The perspective projection transformation, M , used to map 3D objects to the screen is defined by near ($zNear$) and far ($zFar$) clipping planes as only a segment of the volume is visualized at any given time.

$$M = \begin{pmatrix} \frac{f}{aspect} & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & A & B \\ 0 & 0 & -1 & 0 \end{pmatrix} \quad [3]$$

where, $A = \frac{zFar + zNear}{zNear - zFar}$ and $B = \frac{2 \cdot zFar \cdot zNear}{zNear - zFar}$.

In the above equation, $f = \cot\left(\frac{fovy}{2}\right)$ where *fovy* is the field of view angle defined in degrees, and *aspect* is the ratio of width to height.

Thus to determine the coordinates of the 3D surface from the range data stored in the buffer, the inverse transformation is applied.

$$z = \frac{2 \cdot zFar \cdot zNear}{z'(zNear - zFar) + zFar + zNear} \quad [4]$$

We can then determine *x* and *y* from similar triangles as,

$$x = \frac{x' \cdot z \cdot aspect}{f}, \text{ and } y = \frac{y' \cdot z \cdot aspect}{f}. \quad [5]$$

In addition to providing the range map for the current virtual bronchoscope view, it is possible to extract the virtual bronchoscope 3D position (X_c, Y_c, Z_c) with respect to the rendered airway tree, as well as the direction of view defined by the azimuth angle (rotation about the y-axis), the elevation (rotation about the x-axis), and roll (rotation around the z-axis). By exporting these coordinate transformation parameters together with the current digital bronchoscope image, and the range data, it is possible to emulate the virtual bronchoscope position within the rendered airway tree scaled to the real world coordinate space.

5. Intensity correction of digital color bronchoscopy images and display—

Following the determination of the image range values, intensity correction is performed on the *I* component. The resulting correct HSI image is then converted back to the RGB color encoding system for display purposes. If no intensity correction were to be performed then mapping the color information into the 3D space would result in 3D segments exhibiting a gradient in color along the length of the viewing segment (Figure 3). The 2D intensity corrected image is then translated into the 3D real world coordinate space according to the corresponding buffer range values and the projection correction equations as described above. The final multi-modal image fusion results are consequently displayed in a custom interactive 3D software that enables the user to rotate, translate and zoom into the image to fully appreciate the structural forms.

Experimental Methods

3 participants were recruited for participation in this study. 1 of the study participants had a significant smoking history and was exhibiting signs of chronic bronchitis, 1 participant had recurrent respiratory papillomatosis, and a third had a squamous cell carcinoma airway obstruction. Informed consent was obtained from the participants for each of the studies described, in accordance with The University of Iowa Internal Review Board guidelines, and prior to participation in the study. Study participants were scanned on a Philips MX8000 MDCT scanner at total lung capacity (TLC), with a 0.6mm reconstructed slice thickness. Digital video bronchoscopy was performed and recorded on all study participants, and fluorescence bronchoscopy with fluorescein administration was performed on the study participant with squamous cell carcinoma. During this fluorescence bronchoscopy procedure, images were captured of the airway mucosa with a 488 nm laser light to excite the fluorescein. 3 seconds prior to the individual being injected with a bolus of fluorescein the image acquisition commenced and continued for a further 12 seconds. At 12 seconds post injection the laser light

was turned off for a period of 1 minute 30 seconds, turned on for 3 seconds, off for 1 minute, and back on for a final 3 seconds. The motive for the fragmented laser light image collected was to ensure that the airway mucosa was not exposed to the laser light for extended durations. Immediately prior to the acquisition of each of the laser excitation sequences an automated white light bronchoscopy image was taken for registration purposes.

Validation in airway phantom—Experiments have been previously reported that determine the maximum shift in the virtual bronchoscope viewpoint from the digital bronchoscope position that would result in a targeted biopsy needle error of 5mm (16). In the reported application, the registration process was desired to guide a biopsy needle, and thus a needle placement error of 5mm was deemed tolerable. The maximum possible deviation from the desired bronchoscope position was found to be approximately 10mm in translation and 20 degrees in rotation. This registration error however is unacceptable for the fusion of the bronchoscopy and MDCT image datasets and thus we performed a phantom experiment, to assess the accuracy of the registration method to reliably align the two imaging modalities in an ideal environment. It should be noted however, that the error in registration will increase in non-ideal clinical applications, as the lung itself is not a rigid structure and thus will likely not be at an identical 3D structural shape during both MDCT scanning and the bronchoscopy procedures.

To assess the accuracy of the registration method to reliably align the two imaging modalities we performed a simple experiment using an adult rubber airway phantom. Metal beads (1.4 mm in diameter) were placed on the endoluminal wall surface (Figure 4). The phantom was then imaged using both digital color bronchoscopy and MDCT ($0.402 \times 0.402 \times 0.6$ mm resolution) imaging modalities. Six bronchoscopy frames at each of the 4 bead locations were registered with the MDCT generated virtual bronchoscopy. The digital bronchoscopy images, prior to being associated with the virtual bronchoscopy derived range values, were assessed to determine the center pixel bead location within each of the 6 images. The appropriate transformations were then made to the pixel locations to determine their subsequent 3D real world coordinates. These spatial values of the bead locations were then compared to those read directly from the MDCT images.

RESULTS

Two examples of the digital color bronchoscopy and MDCT image fusion process are provided in Figures 5 and 6. One of the example study participants was a smoker with a significant smoking history who was exhibiting signs of chronic bronchitis. Both the structural shape of the airway tree and the digital color bronchoscopy images appear within the normal range in this individual. The second example provided is from a patient with recurrent respiratory papillomatosis. The structural shape of the airway tree in this individual is unmistakably altered with the presence of a large airway obstruction, as is the color of the airway mucosa. In the 2D bronchoscope image the airway appears to be almost entirely occluded, however the fusion of the two imaging modalities shows that there is in fact a clear pathway past the obstruction at that same position.

To demonstrate the future 4D potential of this image registration and subsequent fusion, digital bronchoscopy images were captured of a patient airway using both the digital color and fluorescence detection bronchoscopes (with airway fluorescence augmented by a systemic injection of fluorescein). The 2 complimentary imaging modalities were subsequently fused with the MDCT segmented airway surface rendering. A patient with a significant squamous cell carcinoma airway obstruction was recruited for this study. Immediately following the digital color bronchoscopy procedure, the patient participated in the fluorescein augmented bronchoscopy study. Mutual information image registration was then performed to align the

white light images captured with the fluorescent detection system together with the white light images captured with the color bronchoscopy imaging system. Once the registration transformation was established between the two optical systems, the color image was consequently registered with the MDCT generated virtual bronchoscopy image as previously described. Prior to mapping the digital color image to the MDCT generated airway tree the color image was intensity corrected and merged with the corresponding fluorescein emission images. These image processing steps were performed at a number of time intervals post exposure to fluorescein thus constructing a 4D multimodal description of the pulmonary airways (Figure 7).

Validation in airway phantom

The average error, or Euclidean distance from the actual bead location to the location determined through the registration process for all 6 images of each of the 4 beads (24 registration results in total) was determined to be 1.98 mm.

DISCUSSION

We have demonstrated that we can successfully combine 2D digital bronchoscopy images with surface renderings of the pulmonary airway tree extracted from MDCT image datasets. At this early stage we have only registered single bronchoscope views to the 3D structure. Although this is a preliminary pilot study in the field of endomicroscopy, we can begin to appreciate the possible future power of this field of study.

Figure 4 depicts the registration of the digital bronchoscopy and MDCT extracted data from a patient with a normal appearing airway. This image demonstrates the success of the registration process, however, it also highlights associated limitations. In the warping of the 2D bronchoscope images depth values are found for all pixels in the 2D image. In some instances mucosal surfaces may be too far from the bronchoscope tip and will therefore suffer from poor illumination. Likewise, the illumination may be too intense as a result of specular reflections. In both instances it is difficult to determine accurate mucosal color hue and saturation values. This may lead to mapping of inaccuracies onto the final 3D result providing misleading results. A second limitation of this direct texture mapping process is highlighted in figure 5 where mucosal surfaces are occluded from the field of view of the bronchoscope (virtual or digital). Or when the airway wall surface is at a large distance from the bronchoscope lens resulting in overly stretched (pixelated) images in the merged datasets. In both examples it may be desirable to clip the texture map so that it closely follows the mucosal shell, and to re-image the clipped portion at a more appropriate bronchoscope position.

Validation of the registration and texture mapping process was performed in a rubber human airway phantom. Metallic beads were placed on the phantom wall to provide markers for assessing the registration accuracy. Although the metal beads provide superior contrast in the MDCT images than in the digital bronchoscopy images, this did not affect the registration process as it was performed on the virtual bronchoscopy images (surface renderings of the airway lumen). In the virtual bronchoscopy views the beads appear as a surface irregularity, which should not significantly affect the subsequent registration with the digital color bronchoscope images. The error associated with the registration process was found to be < 2mm, however it is expected that this error would increase *in vivo* due to the movement of the airways in response to respiratory and cardiac motion. The MDCT scans were obtained at TLC, whereas the bronchoscopy images were acquired during normal respiration. This will undoubtedly lead to additional registration errors as a result of the lungs being imaged at different volumes. Continual, repetitive registration of the digital bronchoscope images and the virtual bronchoscopy provided more accurate registration results than isolated image registration. An initial registration is typically made in the trachea. The process is then repeated

for sequential bronchoscope images as the bronchoscope traverses the airways. If the initial registration is not perfect, the margin of error typically will be reduced in the subsequent registration results.

We have demonstrated that merging of three distinct digital datasets to give a single dataset available for viewing is possible. In this manner the physician can visualize and understand complex patient specific structure and function in a single image set. It is hoped that continued research in this field will enable the physician to access all information regarding the central airways quickly and efficiently, including changes over time. We believe that the fully implemented process of eidomics will inform the physician about disease specific behaviour, enabling utilization of increasingly complex multi-modality image data. This will occur in much the same way that the weather map informs us about current and future weather, without us ever having to see the raw data that is collected. We hope that through eidomics a new image based language will develop that may simplify health care delivery.

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Figure 1. Block diagram depicting the major processing steps in the fusion of the digital bronchoscopy images with the structural airway rendering extracted from the MDCT image data.

Figure 2.

The application of the bronchoscope distortion correction to images captured with the digital color bronchoscopy system. A. and C. show images captured with the bronchoscope of a calibration grid, and a patient airway with signs of chronic bronchitis. Image B. and D. show the result of the distortion correction algorithm applied to images A. and C. respectively.

Figure 3.

The figure illustrates the necessity of intensity correction. A. shows the original bronchoscope image, B. the intensity corrected image, and C. and D. show images A. and B. projected into the real world coordinate space.

Figure 4.

A surface rendering of the adult phantom airway from MDCT image data showing the location of the 4 beads together with example digital color bronchoscope images.

Figure 5.
A. A digital color image of the trachea obtained from a patient with a significant smoking history and signs of chronic bronchitis. B. The fusion of the digital color bronchoscope image with the airway tree extracted from the patient's MDCT image dataset.

Figure 6.

A. The digital color image of the trachea from a patient with recurrent respiratory papillomatosis. B. The corresponding digital color image fused to the MDCT based surface rendering.

Figure 7.

This figure represents a series of fluorescein induced airway fluorescence, airway mucosal color, and airway structure through the combination of the 3 imaging modalities. The first set of images (A.) occur 10 seconds post fluorescein administration, (B.) the second set at 100 seconds, and (C.) the third at 160 seconds.