TECHNICAL NOTES

Cinematic Display of Respiratory Organ Motion with Impedance Techniques

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A technique is described for the recording of individual images during discrete phases of the respiratory cycle, i.e., isovolume images. The method is based on the observation that transthoracic impedance is related approximately linearly to lung volume. This impedance signal can be converted to an FM signal to simulate a Z pulse, then added in parallel to the Z pulse from the gamma camera. Simulated X and Y position signals locate simulated Z at the periphery of the computer field of view. Summation of the images with coinciding simulated Z counts produces isovolume images, one for each phase of respiration. These images then can be displayed in cinematic mode or as motion-corrected images. This new technique offers a potential for improved image resolution, temporal separation of organs that exhibit different motion patterns, and estimation of regional pulmonary function.

Respiratory motion is one of several important but uncontrolled factors that limit the resolution of nuclear medicine images of mobile organs. Scintiphotos of the lungs, liver, spleen, and kidneys are generally acquired during periods ranging from 30 to 60 sec. Thus, even in the best of circumstances, these images have been affected by the motion of these organs during 10–20 respiratory cycles.

Several techniques have been suggested in an effort to reduce artifacts due to respiratory motion. Early methods attempted to solve the problem by acquiring data only during a short portion of the respiratory cyle. This was accomplished by breathholding (*1–3*), or by gating with mechanical strain gauges (*4*) or physiological signals (*5*).

Analog circuits have been used to reposition the incoming scintigraphic image on the camera CRT by analysis of the vertical displacement of the data centroid (*6–9*). A similar method uses computer analysis of centroid location to reposition data after acquisition (*10,11*). These methods are limited by the assumption that rotary motion and plasticity of the imaged organ are negligible.

Other methods have utilized computer acquisition and processing to generate cinematic displays of organ motion. Changes in lung volume, as measured by spirometer, can be recorded simultaneously during a dynamic acquisition, then used to reconstruct isovolumetric images (*12–14*). A corrective algorithm must be used for spirometer drift due to gas leakage, oxygen consumption, and CO_2 output. Furthermore, patients with lung disease may find it difficult to breathe through systems with significant airway resistance. Line et al. (*15*) have used pneumotachometry to min-

imize problems associated with a resistive system and to provide potentially useful information regarding the pressure/volume relationship during respiration. Patient cooperation, gas leakage, and oxygen consumption still present problems. Kaplan (*16*) using Kr-81, and Touya et al. (*12*) using Xe-133, analyzed time-activity curves derived by recording over the lungs to obtain isovolumetric images. These techniques do not require additional apparatus for measuring volume changes but are limited to ventilation imaging and require substantial doses of radioactivity for adequate counting statistics in the individual images.

The technique described here uses an impedance plethysmograph to monitor the respiratory cycle. It enables one to study extremely ill patients without using a spirometer or pneumotachometer, and minimal patient cooperation is required. The impedance changes are recorded along with organ images during a dynamic study acquisition. The isovolume images are reconstructed by the computer and can be displayed in cinematic mode. Functional information can be obtained to evaluate global and regional ventilation and pulmonary motion.

METHODS

A system was designed for obtaining isovolumetric images of mobile organs. It consists of (a) an impedance plethysmograph,* (b) a circuit that makes the output compatible with a standard nuclear medicine computer system, and (c) a computer program for reconstructing the isovolumetric images.

Impedance plethysmography. The impedance plethysmograph has been used by several investigators to monitor respiratory volume (*17–19*). It has been shown that electrical impedance changes correlate nearly linearly with volume changes as recorded by a spirometer. The optimal location of the electrodes for best linearity
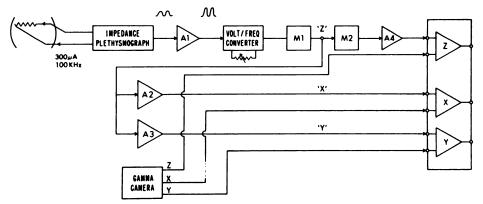
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FIG. 1. Block diagram of circuit. See text for description.

appears to be the anterior axillary line at the level of the manubrium sterni (19).

This monotonic relationship between lung volume and impedance change permits the impedance-plethysmograph curve to be used as an approximate indicator of the patient's lung volume.

Description of the circuit. The circuit (Fig. 1) was designed to convert the amplitude-modulated dc output from the plethysmograph to simulated Z signals and to generate simulated X and Y signals to locate Z at the periphery of the field of view (Fig. 2). The output of the plethysmograph is fed into an isolation operational amplifier (A1), then passed through a voltage-to-frequency converter where signals indicating higher impedance produce more Z pulses per second, and vice versa. Potentiometers allow the operator to adjust the range and pulse frequency so that the pixel used to record the respiratory data (at a frame rate of 3–4 per sec) will not be saturated. The signal passes through a monostable multivibrator (M1) producing a 6-μsec pulse that generates X and Y via two isolation operational amplifiers (A2,A3) located next to the computer. The output of M1 is also fed into a second monostable multivibrator (M2) and a gain (×2) operational amplifier (A4) producing a 6-V 2-μsec pulse. This pulse is compatible with the Z input electronics of the computer and can be added in parallel to the Z pulse from the gamma camera. Thus, the computer records a count rate that is the sum of counts from the patient image and "counts" generated by the circuit. A region of interest can be drawn around the location of the respiratory signal, Z, and a time-activity curve then generated from all of the acquired frames (Fig. 3).

Computer analysis. The computer program was designed to create ten isovolumetric images, each of which represents patient data obtained during a discrete phase of respiration.

The entire range of electrical impedance values, as represented by the amplitude of the "time-activity" curve, is divided into ten equal volume divisions. Each frame in the study is then assigned to one of ten bins, depending on the value of the curve at that time. Ten new frames are obtained by summing the data from all of the frames in each of the ten bins.

The number of image frames in each bin is checked, and the summed frames are normalized to account for differences in the number of frames in each bin, by the formula:

$$CFx = \frac{\text{max. no. of frames in any bin}}{\text{no. of frames in bin x}},$$

where CFx = correction factor for bin x.

Variations in respiratory patterns may cause bins 1 and/or 10 to have an unacceptably low number of frames. Therefore, normalization factors for these summed frames may be very high, and the resulting normalized image may be "noisy." To avoid this problem, the normalization factors for Bins 1 and 10 are compared with the others. If either CF 10 or CF 1 is greater than 2.5, the entire range is reduced by half of a bin-width by eliminating half of the offending bin. The new range is then redivided into ten bins, and the entire analysis is repeated. When acceptable summed frames are obtained, they are interpolated and smoothed. They are stored for cinematic display by recording them in ascending order, followed by descending order, to simulate a respiratory cycle. Rejected data generally account for less than 5% of the total of acquired data. Larger data losses were noted only when artifacts were introduced because of unusual patient motion, such as that induced by coughing.

Phantom study. The smearing artifact from respiration was demonstrated with a thyroid phantom and 6 cm of pressed wood as scatter material. Respiratory organ motion was simulated by analog images that were acquired at eight successive 2-mm displacements for a total displacement of 16 mm. Since areas of the liver may move as much as 25 mm, this represented a reasonable excursion. Images were made with an all-purpose collimator, and the simulated motion study was performed at two different information densities, 1000 counts/cm^2 to simulate a lung image, and 2000 counts/cm^2 to simulate a liver image.

Patient studies. Twenty-one patients underwent liver-spleen scintigraphy, 20 images being evaluated for possible mass lesions of the liver and one for trauma to the spleen. Fourteen patients had
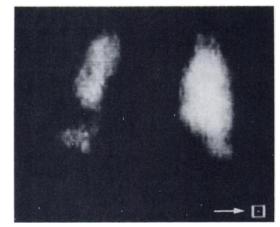

FIG. 2. Summed image of 30 frames from ventilation study. Respiratory signal is carried in pixel outside camera's field of view, with regular region of interest drawn around it (arrow). Amplitude of respiratory signal will fluctuate corresponding to temporal changes in lung volume.
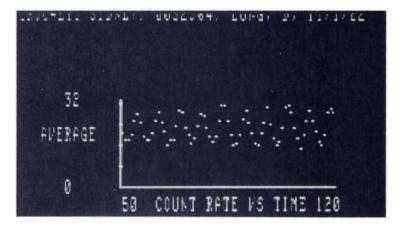
FIG. 3. Time-activity curve generated from region of interest shown in Fig. 2. With proper placement of electrodes, impedance changes will vary approximately linearly with lung volume changes. This curve represents cycling lung volume during 50 frames (17 sec of respiration).

normal studies; three had diffuse hepatic disease with colloid shift; one had a splenic hematoma, and four had defects of the liver. Twenty-eight patients had pulmonary perfusion images, performed in either the anterior or posterior view. In addition, 12 of these patients underwent ventilation studies. Twenty-four of these patients were studied because of suspected pulmonary embolism. Four patients with chronic asthma also were evaluated, before, during, and after administration of bronchodialators.

Liver studies were performed using 3 mCi of Tc-99m sulfur colloid; perfusion lung studies used 3 mCi of Tc-99m macroaggregated albumin, and a standard 4-mCi Rb-81 → Kr-81m generator system for ventilation imaging.

Following the routine study, a single view was selected for the respiration-monitored acquisition. Ag-AgCl electrodes were placed in the anterior axillary line at the level of the manubrium. All liver images were obtained with the patient supine. Lung images were obtained in the sitting position when possible; otherwise, the patient was supine on a Plexiglas table, with the detector below. To avoid artifacts in the impedance signal, each patient was instructed not to move his hands or arms during the procedure, but no attempt was made to regulate respiration. Images were obtained using an all-purpose parallel-hole collimator and an LFOV camera interfaced to a standard nuclear medicine computer system. Each study was recorded in dynamic mode at 3 frames per sec for 500 sec, using a 64- by 64-byte matrix.

Total accumulated counts for Tc-99m sulfur colloid studies and Tc-99m MAA perfusion lung studies were between 3.5 and 4.5 million. Ventilation lung studies with Kr-81m contained 1.2 to 1.5 million counts, depending primarily upon the time of day (age of generator) and the patient's pulmonary functional status.

Functional information may be derived from the temporal activity changes demonstrated in the isovolume images. Following generation of isovolume lung ventilation images, an ROI can be drawn around each lung (Fig. 4, upper), and using a standard routine for cardiac ejection fraction, a lung-volume curve (Fig. 4, lower) and an expiratory fraction for each lung can be obtained.

RESULTS

Phantom study. Figure 5 illustrates analog images from the phantom study. The single-position images have one ninth the number of counts of the summed images and have been normalized for display purposes. Despite the lower number of counts, the single-position images, A and C, clearly delineate the 1.2-cm foci of decreased activity while the 9-position summed images, B and D, demonstrate degraded resolution. In the summed image, the photon-deficient defects could be interpreted mistakenly as thinning or a larger defect. For images of both high (liver) and low (lung) information density, the simulated respiratory artifact produces an obvious reduction in resolution.

When these nine different position images are recorded as static images on the computer in 128 × 128 matrix and are played back in a cinematic display, there is an additional improvement in resolution over the static computer image. Observers are able to follow clearly the motion of the well-defined photopenic defects, which suggests that cinematic display of organ motion may also help the observer to separate target from nontarget activity.

Patient studies. Among the 14 patients with normal liver studies, the cinematic images demonstrated motion of the liver and spleen, but did not alter interpretation of the studies. Three patients had diffuse hepatic disease with colloid shift. Again, no significant
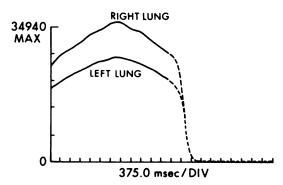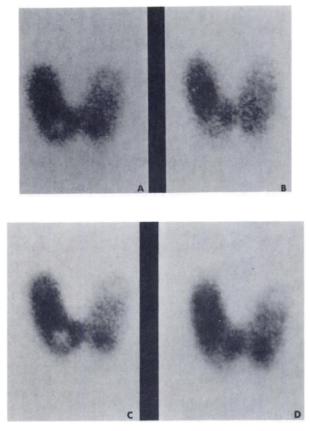

FIG. 4. Regional ventilatory function can be evaluated by analyzing data from all ten of the composite frames. Figure 4, upper shows regions of interest drawn around each lung in a ventiation study. Curves in Fig. 4, lower represent time-activity curves obtained when routine processing for cardiac ejection fraction is applied to these data. Using this technique, information regarding individual lungs or sections of lung may be obtained.

FIG. 5. Analog images from phantom study. Using an all-purpose collimator, nine static images were acquired at 2-mm displacements, both (a) at information density of 1000 counts/cm² to simulate a lung image, and (b) at 2000 counts/cm² to simulate a liver image. 5A, one of static images at ID = 1000; 5B, corresponding sum of nine static images; 5C, one static image at ID = 2000; and 5D, sum of these nine images. Note improved resolution of the 1.2-cm photopenic areas (lower pole on viewer's right) that results when effects of motion are removed. This improvement occurs for images of both high and low density. Storage of these displacement images in a computer, with display in cinematic mode, appears to further improve recognition of defects.

improvement in diagnosis was obtained using the cinematic display. One patient had a splenic hematoma that was seen better on the analog images. We note that the cinematic images for this patient demonstrated no significant motion of the spleen, which accounts for the superior resolution of the analog views. The remaining four patients had defects in the liver. During formal evaluation of the technique, the cinematic display showed one lesion that was not appreciated on the analog views. This defect was confirmed in retrospect on the analog views by several observers.

Figure 6 shows a comparison between the summed data from all frames and the end-exspiratory summed data in a patient with liver metastases. As in the phantom study, the random noise in the low-count images is significantly reduced when these images are displayed in cine mode, thereby further improving the liver-image resolution.

Analysis of the ventilation and perfusion images in cinematic and analog display yielded no significant differences. Evaluation of the four patients with chronic asthma also resulted in no significant differences between the analog and cinematic displays. The ventilation studies also were evaluated by drawing regions of interest around each lung, and by using the routine for cardiac ejection fraction, the percentage of activity exhaled during respiration was measured. Expiratory fractions were generally lower in these four patients than in the other 12, and rose in three out of four patients after the administration of bronchodilators. No changes after bronchodilation were seen in the analog images.

DISCUSSION

Respiratory motion is responsible, in large part, for the limited resolution of some radionuclide images. This image degradation can be minimized either by restricting organ motion, using techniques such as breath holding, or by acquisition during only a small part of the respiratory cycle. The technique described here allows sorting of data solely on the basis of relative lung volume during the acquisition of each frame. Each resulting image is the sum of data acquired at similar lung volumes, and is therefore of superior quality. The cinematic display that can be generated from these data can be used to evaluate organ motion and, in the case of the lungs, to measure changes in volume.

The technique is similar to the method described by Touya et al. (12), who use a pneumotachometer to take advantage of the

FIG. 6. Images taken from 78-yr-old woman with colonic cancer. At left is end-exspiratory frame. Right: summed data from all 1500 frames. Former has sharper margins and shows better definition of defects despite lower count density (20% of the data).

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additional information provided by flow-volume loops. However, many severely ill patients cannot use a breathing apparatus for a prolonged period of time, and similar isovolume images can be obtained using an impedance plethysmograph.

Phantom work with a thyroid phantom in the presence of scatter clearly demonstrates an improvement in resolution for both the single-position images and the cinematic display. The latter improves resolution, (a) by moving count profiles across computer pixel borders, and (b) by the observer's ability to recognize motion pattern (borders) and distinguish this from noise. (20) Presenting the cinematic display at 5-10 images/sec permits the visual system's integration time constant of approximately 100 msec to assist in filtering out the random noise.

Translational and rotational motion, besides plastic deformation of the liver and spleen, can be demonstrated in the cine. Some livers exhibit larger excursions than others, and this information may be of value in differentiating thinning artifacts due to motion from true photopenic areas.

Besides improving resolution, cinematic display may allow differentiation of one organ from another by identifying different motion patterns. In hepatobiliary imaging, for example, motion may cause blurring of a faintly visualized gallbladder, making it indistinguishable from liver activity or other background. It may be possible to improve visualization of this low-level source of activity by separating out the motion of the gallbladder from that of overlying biliary structures.

Application of this technique to the measurement of pulmonary function may provide information of pathophysiologic significance. Standard tests of pulmonary function yield volumes and flow rates for both lungs, but the contribution of each lung is impossible to discern without invasive techniques. Using measurements of the expiratory fraction of each lung, we can estimate the tidal volume of each lung by multiplying the fractional contribution of each by the measured tidal volume. The potential importance of such information is immediately apparent. Many lung diseases are inhomogeneous in their distribution and may even be confined to one or several areas of the lungs. The ability to locate disease and determine specifically whether or not a region of the lungs responds to therapy would be valuable.

The possibility of measuring regional pulmonary function suggests a new area of investigation. The responses of various portions of the lungs to physiologic or pharmacologic interventions may have important diagnostic and therapeutic implications. This kind of study may be useful to test drugs used in the treatment of pulmonary disease, to evaluate the regional effects of exercise on normal and abnormal pulmonary function, to evaluate the contribution of lung disease in a patient with symptoms of cardiopulmonary abnormalities, and to evaluate the potential candidate for pulmonary surgery.

The clinical significance of improved resolution using this technique is being evaluated. It seems likely that with refinements of the method—including larger matrix size and more rapid or real-time processing—this type of study may have useful clinical applications.

FOOTNOTE

* Brattle Physiological Synchronizer, Brattle Instrument Corp., Cambridge, MA 02139.

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