# RESOLUTION CAPABILITY OF A MULTIPROBE SYSTEM FOR DETERMINING REGIONAL LUNG PERFUSION WITH $^{133}$XE

Murugappan Ramanathan and James E. Wilson III

*University of Texas Southwestern Medical School at Dallas, Dallas, Texas*

***The resolution capability of a multiprobe scintillation detector system is determined by occluding branches of the pulmonary arteries in dogs by means of a double-lumen balloon-tipped catheter. Regional pulmonary blood flow is estimated in terms of regional perfusion indices with a breath-holding method using $^{133}$Xe. The perfusion studies are done before (control) and after creating the occlusion. The percent decrease in perfusion index as a result of the occlusion is calculated from experimentally obtained perfusion indices. Based on the distribution of the radioactivity present before and after the occlusion, a theoretical relationship is derived for percent decrease in perfusion index due to the occlusion. The percent decrease in perfusion index can be predicted from the thickness of the occlusion, the depth from the face of the collimator to the beginning of the occlusion, the proximal distance of the lung tissue from the face of the collimator, AP diameter of the lungs, perfusion gradient per unit blood flow at the proximal edge of the lung along the axis of the collimator, and the linear attenuation coefficient of $^{133}$Xe in the lung tissue. The predicted percent decrease in perfusion index correlates well ($r = 0.91$) with the experimentally obtained percent decrease in perfusion index.***

Radioactive xenon has been used since 1955 (*1*) to determine regional lung function. It is clear that the xenon technique can detect large perfusion defects or large ventilation defects. However, the limits of resolution of the technique are not clearly established and the effect of depth of a given size occlusion within the lung is not known. The purpose of the present study was to determine the resolution capability of the multiprobe xenon technique by means of occluding various-sized branches of pulmonary arteries with balloon-tipped catheters, and to assess the effect of the depth and the thickness of the occlusion on the resulting change in the perfusion index in that region.

## MATERIALS AND METHODS

Mongrel dogs weighing 25–40 lb were anesthetized with pentobarbital 13 mg/lb intravenously. This was supplemented at 1–2-hr intervals with 65–130 mg when required to avoid spontaneous respiratory efforts. The dogs were intubated and were ventilated with a Harvard volume ventilator set at a tidal volume of 10 cc/lb and a respiratory rate of 8. This was found to give an approximately normal arterial $pCO_2$. A dog was placed in the supine position and was fluoroscoped in the position in which it remained for the subsequent studies. Markings were made over the chest in the appropriate location for scintillation probes to be placed, as shown in Fig. 1.

Regional perfusion was determined with a multiprobe detector system for $^{133}$Xe similar to that described by Ball, et al (*2*). Four scintillation counters were placed over each lung field posteriorly and were collimated with cylindrical collimators 1¼ in.

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For reprints contact: James E. Wilson III, Cardiopulmonary—D-710, 5323 Harry Hines Blvd., Dallas, Tex. 75235.

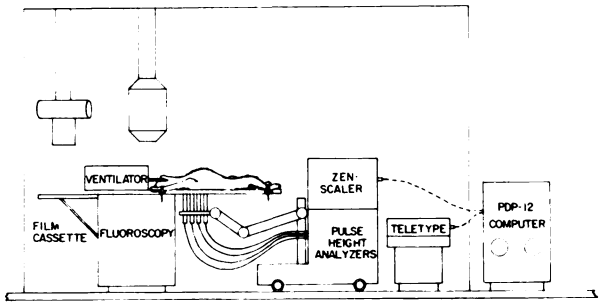


**FIG. 1.** Experimental setup used.

in diameter and 7 in. long. The diameter of field of view at 6 cm away from the face of the collimator is 5.33 cm and is 11.76 cm at 24 cm. Signals from each scintillation detector were directed to a Picker pulse-height analyzer (Model 628056). A window, centered on 81-keV gamma rays of $^{133}Xe$, was adjusted so that each detector gave the same counting rate when directed toward a $^{133}Xe$ source of uniform activity. The output of each pulse-height analyzer was connected to a local interface (Zen-Scaler-15, Zentron Inc., Dallas, Tex.) where counts from each detector were accumulated for 1-sec intervals. These counts were transmitted on-line to a Digital Equipment Corp. PDP-12 digital computer under program control.

A perfusion index was calculated as the fraction of total counts from a region after a bolus infusion of $^{133}Xe$ divided by the fraction of total counts from the same region during ventilatory equilibration when $^{133}Xe$ concentration was the same everywhere within the lung (*3*). A teletype printout of the perfusion indices was available immediately following the procedure.

A ventilatory equilibration with $^{133}Xe$ in a closed system was carried out by connecting the inspiratory and expiratory lines of the volume ventilator to a spirometer containing $^{133}Xe$, a $CO_2$ absorber, and a mixing motor. Counting rates from each region were obtained after full equilibration with $^{133}Xe$. Following control perfusion indices, a branch of the pulmonary artery was occluded by means of a double-lumen balloon-tipped catheter (Swan-Ganz, Edwards Lab., Santa Ana, Calif.). The perfusion indices were repeated with the occlusion in place. The method is very reproducible with an average coefficient of variation of 3.3% (*4*). To identify the detectors that were seeing the occluded regions, $^{133}Xe$ (0.5–1.5 mCi) was injected through the distal lumen into the occluded region of lung. In all cases except one, over 75% of the counts following local injection were seen in no more than one or two of the counters. In order to quantitate the size of the occlusion, selective angiograms were obtained by means of injecting Renografin-76 (E. R. Squibb & Sons, Inc.) and obtaining an AP and lateral x-ray film of the chest with the breath held at the same lung volume at which all other studies were performed.

## ANALYSIS METHODS

The regional perfusion index estimated before and after the occlusion indicates the relative blood flow without and with the occlusion. The observed percent decrease in perfusion index (PDPI) as a result of the occlusion is calculated as the percent decrease in the experimentally obtained perfusion indices

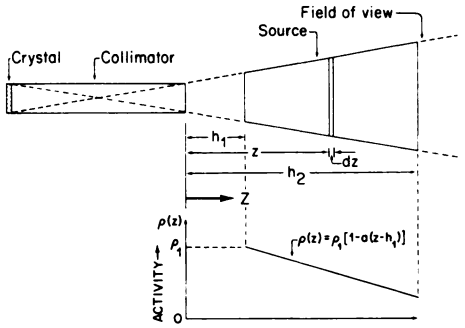


**FIG. 2.** Geometry of source and collimator. $h_1$ and $h_2$, Proximal and distal distance of lung from face of collimator.

from the control value using the following relationship:

$$PDPI = (PI_{ci} - PI_{oi})/PI_{ci} \times 100 \qquad (1)$$

where $PI_{ci}$ is the perfusion index of $i^{th}$ region during control study before occlusion, and $PI_{oi}$ is the perfusion index of $i^{th}$ region after occlusion.

Within the field of view of a single collimator, the effect of depth and the thickness of cold volume within a hot-volume source of known activity distribution has been explained from a relationship derived for percent decrease in perfusion index in the following manner.

The response of a collimated detector can be calculated for an assumed activity distribution and the sensitivity distribution of the collimated detector. When a plane source of uniform activity is located in front of a detector, the counting rate is found to be independent of the distance between the source and the face of the collimator (*5*). This is true only when (A) the plane source covers the entire field of view at any depth, (B) there is no attenuation within the source, and (C) the penetration and scatter are negligible. The counting rate (R) due to a plane source of uniform density ($\sigma$) can then be written as

$$R = k\sigma$$

where k is a constant.

The fact that the plane-source response is constant, independent of depth, can be used to find the response to a volume source (*6,7*).

Consider a volume source covering the entire field of view placed in front of a collimated detector as shown in Fig. 2. Let $h_1$ and $h_2$ be the proximal and distal edge of the source from the face of the collimator. The activity gradient within the lung varies as the perfusion per unit volume within the lung. The perfusion per unit volume increases linearly from the distal to proximal edge in the direction of gravity (*8*). Let the activity per unit volume at the proximal edge in a supine dog be $\rho_1$ and the activity gradient be $\alpha\rho_1$. Then the activity per unit volume $\rho(z)$ at any

distance z from the face of the collimator may be written as

$$\rho(z) = \rho_1[1 - \alpha(z - h_1)] \quad \text{for} \quad h_1 \leq z \leq h_2$$
$$= 0 \qquad\qquad\qquad\qquad \text{otherwise}$$

Consider a thin slice of thickness dz at a depth z from the face of the collimator. The plane source density for this slice will be $\rho(z)dz$ per unit area. The radiation from this thin slice will be attenuated by a factor $e^{-\mu(z-h_1)}$ where $\mu$ is the linear attenuation coefficient of the source. The effective plane source density ($d\sigma$) for this thin slice will be

$$d\sigma = \rho(z)\, e^{-\mu(z-h_1)}\, dz$$

Taking the attenuation into account, the effective or equivalent plane source density for the whole volume source ($\sigma_c$) becomes

$$\sigma_c = \int_{h_1}^{h_2} \rho(z)\, e^{-\mu(z-h_1)}\, dz$$
$$= \int_{h_1}^{h_2} \rho_1[1 - \alpha(z - h_1)]\, e^{-\mu(z-h_1)}\, dz$$
$$= \frac{\rho_1}{\mu}\left\{1 - \frac{\alpha}{\mu} + e^{-\mu(h_2-h_1)}\left[\frac{\alpha}{\mu} + \alpha(h_2 - h_1)\, 1\right]\right\}$$

The counting rate ($R_c$) due to the volume source will be

$$R_c = k\sigma_c$$

Now consider the same volume source with a complete occlusion present in a region between $d_1$ and $(d_1 + T)$ as shown in Fig. 3. When there is a complete occlusion in a region, the activity in the occluded region will be zero as there cannot be any xenon in that region. The activity distribution can now be written as

$$\rho(z) = \rho_1[1 - \alpha(z - h_1)] \quad \text{for} \quad h_1 \leq z \leq d_1$$
$$\text{and for} \quad d_1 + T \leq z \leq h_2$$
$$= 0 \qquad\qquad\qquad\qquad \text{otherwise}$$

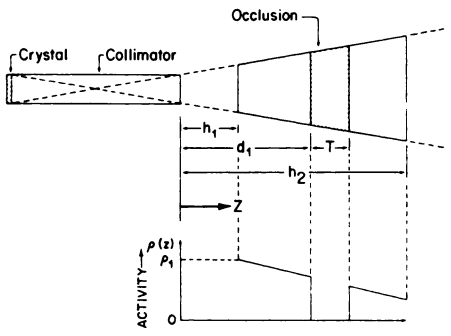


**FIG. 3.** Geometry of source and collimator with occlusion. $h_1$ and $h_2$, Proximal and distal distance of lung from face of collimator; $d_1$, distance between face of collimator and beginning of occlusion; T, thickness of occlusion.

With a complete occlusion present, the equivalent plane source density

$$\sigma_0 = \int_{h_1}^{d_1} \rho(z)\, e^{-\mu(z-h_1)}dz + \int_{d_1+T}^{h_2} \rho(z)\, e^{-\mu(z-h_1)}dz$$
$$= (\rho_1/\mu)\left\{e^{-\mu(h_2-h_1)}\left[\frac{\alpha}{\mu} + \alpha(h_2 - h_1) - 1\right] - \frac{\alpha}{\mu} + 1\right\} - (\rho_1/\mu)\, e^{-\mu(d_1-h_1)}$$
$$\left\{(1 - e^{-\mu T})\left[1 - \frac{\alpha}{\mu} - \alpha(d_1 - h_1)\right] + \alpha T\, e^{-\mu T}\right\}$$

The counting rate ($R_0$) with occlusion present within the source will be:

$$R_0 = k\sigma_0$$

The percent decrease in perfusion indices (PDPI) is calculated from

$$\text{PDPI} = [(R_c - R_0)/R_c] \times 100$$
$$= [(k\sigma_c - k\sigma_0)/k\sigma_c] \times 100$$
$$= [(\sigma_c - \sigma_0)/\sigma_c] \times 100$$

Thus the percent decrease in equivalent plane source densities before and after the occlusion directly reflects the percent decrease in perfusion index. Hence, the predicted

$$\text{PDPI} = \frac{e^{-\mu(d_1-h_1)}\left[(1 - e^{-\mu T})\left\{1 - \frac{\alpha}{\mu} - \alpha(d_1 - h_1)\right\} + \alpha T\, e^{-\mu T}\right]}{1 - \frac{\alpha}{\mu} + e^{-\mu(h_2-h_1)}\left\{\frac{\alpha}{\mu} + \alpha(h_2 - h_1) - 1\right\}} \times 100 \qquad (2)$$

where $d_1$ is the distance between the face of the collimator and the beginning of the occlusion; T is the thickness of the occlusion; $h_1$ is the proximal distance of the lung from the face of the collimator; $h_2$ is the distal distance of the lung from the face of the collimator; $\mu$ is the linear attenuation coefficient of lung tissue for $^{133}Xe$; and $\alpha$ is the perfusion gradient per unit blood flow at the proximal edge in the lung.

## RESULTS

The relationship between the observed and predicted percent decrease in perfusion indices is shown in Fig. 4, where $r = 0.91$ ($p < 0.001$). The percent decrease in perfusion index is predicted from Eq. 2 using the data in Table 1. The thickness T of the occlusion, the depth $d_1$, and the AP diameter ($h_2 - h_1$) of the lung are obtained from the lateral selective angiogram (Fig. 5). The linear attenuation coefficient ($\mu$) of 0.046/cm was determined experi-

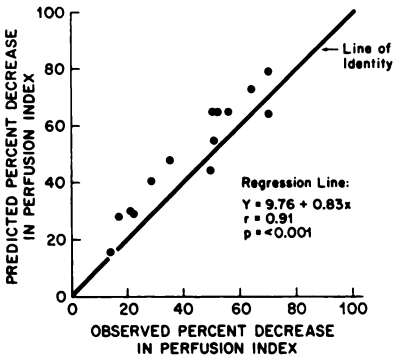


**FIG. 4.** Relationship between predicted and observed percent decrease in perfusion index with breath-holding method using data from Table 1.

mentally by placing isolated lobes of different thickness between the detector and a point source. This value agrees well with the theoretically calculated value of 0.04 assuming a lung density of 0.221 gm/cc (*9*) and a linear mass attenuation coefficient for water at 81 keV to be 0.18 $cm^2/gm$ (*10*). The perfusion gradient along the axis of the collimator for supine dog is determined by measuring perfusion indices at three different heights from the back of the lung, utilizing scintillation detectors oriented horizontally. With the value of perfusion index obtained at three different heights, a straight line is fitted by the method of least squares. The value of $\alpha$ is calculated by dividing the slope of this fit by the perfusion index at the proximal edge. The average value of $\alpha$ obtained in two dogs was 0.044/cm.

## DISCUSSION

The quantitative effect of both the depth and the size of an occluded region on the resulting perfusion index as detected by a multiprobe system is explained by Eq. 2. The predicted response of a detector or the regional counting rate has been calculated from the activity distribution within the lungs and the sensitivity distribution of the collimated detector. The assumptions made in calculating the regional counting rates are explained under analysis methods. A relationship is developed for predicted percent decrease in perfusion index due to an occlu-

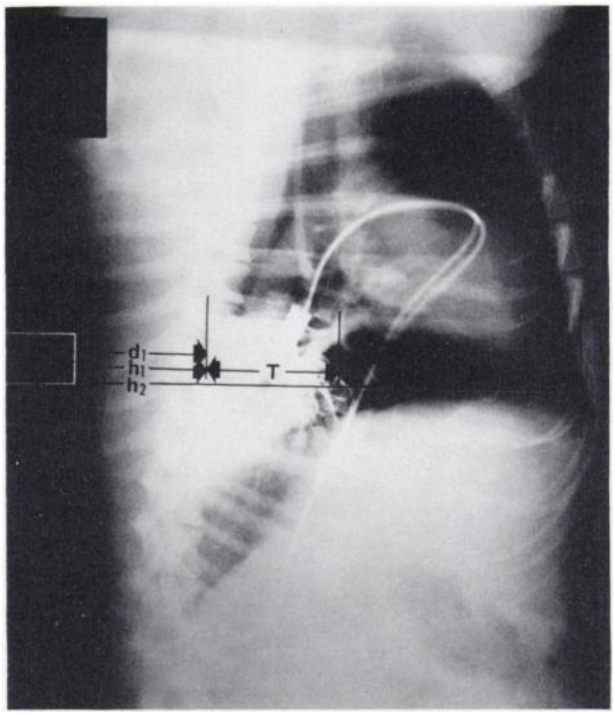


**FIG. 5.** Lateral chest roentgenogram of dog indicating measurements made for calculating predicted percent decrease in perfusion index.

**TABLE 1. MEASUREMENTS OBTAINED FROM LATERAL CHEST ROENTGENOGRAMS TO CALCULATE PREDICTED PDPI FOR AN OCCLUSION IN A SINGLE REGION AND COMPARISON WITH OBSERVED PDPI FOR THAT REGION**

| Dog (No.) | Region* | $h_1$ (cm) | $d_1$ (cm) | T (cm) | $h_2$ (cm) | Predicted PDPI† | Observed PDPI† |
|---|---|---|---|---|---|---|---|
| 4 | $L_3$ | 8.5 | 8.5 | 7.5 | 31.5 | 45.8 | 50.0 |
| 4 | $L_4$ | 7.0 | 7.4 | 4.5 | 13.5 | 71.1 | 63.9 |
| 6a | $L_4$ | 6.0 | 6.3 | 3.5 | 10.5 | 78.4 | 70.4 |
| 6b | $R_3$ | 7.4 | 11.0 | 2.0 | 27.2 | 13.2 | 14.0 |
| 8 | $L_3$ | 7.5 | 7.5 | 5.5 | 23.5 | 43.7 | 51.2 |
| 11a | $R_1$ | 9.1 | 14.5 | 4.0 | 19.0 | 35.4 | 21.0 |
| 16 | $R_4$ | 6.5 | 6.5 | 3.0 | 11.5 | 62.9 | 56.0 |
| 20 | $L_4$ | 6.5 | 9.5 | 3.5 | 21.0 | 26.8 | 22.0 |
| 33 | $R_1$ | 11.0 | 14.5 | 5.0 | 21.0 | 47.1 | 49.4 |
| 34 | $L_3$ | 5.5 | 7.0 | 4.6 | 21.5 | 34.6 | 28.4 |
| 35 | $L_3$ | 5.0 | 6.6 | 5.8 | 21.5 | 41.4 | 35.1 |
| 36 | $R_4$ | 6.8 | 11.0 | 4.0 | 22.4 | 26.8 | 16.8 |
| 37 | $R_4$ | 7.0 | 7.0 | 7.0 | 23.2 | 53.2 | 51.9 |
| 38 | $L_3$ | 7.0 | 7.0 | 7.0 | 23.5 | 52.6 | 69.2 |

* $R_1$, right apex; $R_2$ and $R_3$, right middle; $R_4$, right base. $L_1$, left apex; $L_2$ and $L_3$, left middle; $L_4$, left base.
† PDPI, percent decrease in perfusion index.

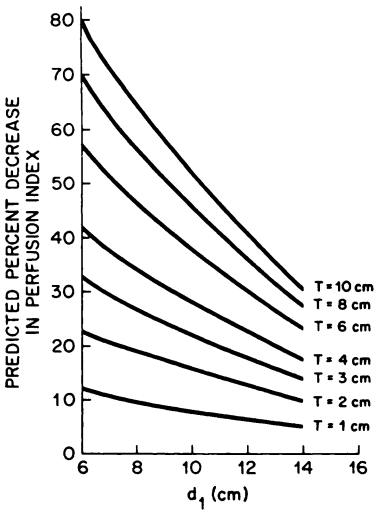


**FIG. 6.** Predicted percent decrease in perfusion index at different depth for different occlusion thicknesses. Assuming $h_1 = 6$ cm and $(h_2 - h_1) = 18$ cm, predicted percent decrease in perfusion index is calculated using Eq. 2.

sion from the theoretically predicted regional counting rates. A comparison between the predicted and experimentally observed percent decrease in perfusion index is made in Fig. 4. The predicted PDPI is a function of the thickness of the occlusion (T), the depth from the face of the collimator ($h_1$), anterior–posterior diameter of the lungs ($h_2 - h_1$), perfusion gradient per unit blood flow at the proximal edge of the lung along the axis of the collimator ($\alpha$), and the linear attenuation coefficient of $^{133}$Xe in the lung tissue ($\mu$). In the supine position with posterior detectors both the attenuation of gamma rays within the lung tissue and the vertical perfusion gradient exaggerate the effect of an occlusion that is closer to the face of the collimator.

Using Eq. 2, the predicted percent decrease in perfusion indices due to a complete occlusion is shown in Fig. 6 with occlusion thickness as a parameter for different depths. The distance between the face of the collimator and the proximal edge of the lung (included a table thickness of 2 cm) was assumed to be 6 cm and the AP diameter was assumed to be 18 cm, which are the normal values in the middle zone of the lung for the experimental dogs. As an example, an occlusion starting at a depth of 7 cm from the face of the collimator must be 2 cm thick to cause a 21% decrease in perfusion index.

From Fig. 6, given an observed percent decrease in perfusion index, one can estimate the thickness of lung tissue that has to be completely occluded at different depths from the face of the collimator. It can also be seen that a given thickness of lung tissue (T) occluded produces less percent decrease in perfusion index when the occlusion is at greater depth ($d_1$). Therefore, in the supine position posterior scintillation detectors have greater resolution capability for perfusion defects that are close to the face of the collimator.

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