Performance Evaluation of Xenon-133 Inhalation Rebreathing Systems for Regional Blood Flow Measurements

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A quality-control phantom is described which is capable of testing the performance of inhalation rebreathing systems for measurements of regional cerebral blood flow (rCBF). The phantom is designed so that data similar to those from a patient study are obtained. The standard rCBF data-processing algorithm is used for the calculation of phantom study results. Malfunctions were induced to simulate instrument malfunction, and their effects on detector and air curves were evaluated. The use of this phantom is recommended prior to a patient study if the rCBF instrument is used infrequently or after service for routine maintenance or malfunction.

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Several commercial multidetector systems for measurement of regional cerebral blood flow (rCBF) by xenon-133 (^{133}Xe) clearance are used in different laboratories for research and clinical measurements. The atraumatic rCBF techniques based on ^{133}Xe inhalation and washout measurements for estimation of gray matter flow (fast flow) have gained clinical interest during recent years (*1–3*). The method allows simultaneous bilateral measurements of rCBF, thus enabling an unaffected hemisphere to serve as a control for an affected one.

Standard commercial instruments consist of an automated xenon administration and rebreathing system, which includes a xenon trap, a ^{133}Xe monitor in the circulating air, up to 32 external collimated counting probes, and a data-analyzing computer. The software for calculation of blood flow from the washout curves uses the two-compartment, one-artifact model described by Obrist et al. (*2*) and Risberg et al. (*3*). From such a study, two types of curves are obtained: an air curve and the external-detector curves.

The concentration of ^{133}Xe in a sample of the inspired and expired air is measured from an air sample drawn through a thin catheter located close to the patient's mouth (face mask) and is recorded by a separate scintillation detector. This curve is referred to as an air-detector recording curve. The end-tidal values of this air curve constitute a reliable estimate of the arterial concentration of ^{133}Xe and are used to correct the head-detector curves for the recirculation of the tracer. The detector curves from the head detector reflect ^{133}Xe activity during ^{133}Xe breathing and the washout of isotope after ^{133}Xe administration is stopped.

The xenon delivery and rebreathing unit has many movable parts (valves) and internal circulation aids to control gas flow. All of these need periodic performance controls to assure measurements of required accuracy and reproducibility, particularly in longitudinal studies.

Phantoms designed to evaluate the accuracy of blood flow measurements are complicated, difficult to maintain, and generally not available. In contrast, a phantom to test the mechanical function of the ^{133}Xe delivery and rebreathing system and to check the performance of air-curve detector and the external head detectors can be constructed more easily. Since such a phantom is not currently available commercially, a mechanical or electronic malfunction may be detected only during a patient study. In order to determine whether a given system is operating correctly before a patient study, it is desirable to perform the entire study, including the data calculation, with an easily accessible and manageable phantom.

We describe a phantom that we have used routinely and present the characteristic malfunction patterns ob-

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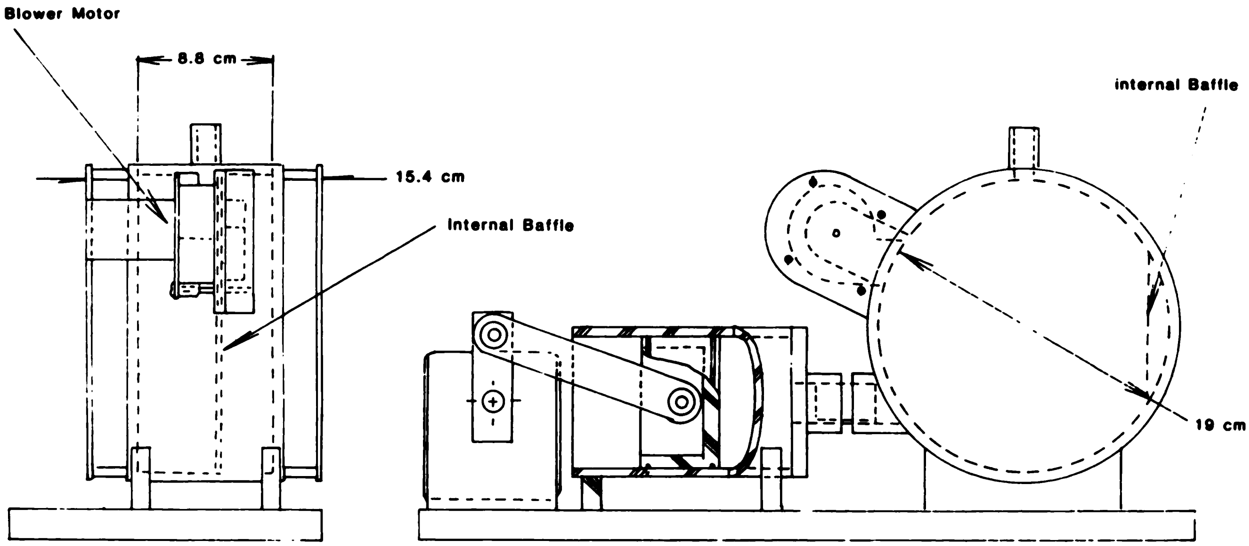

FIGURE 1
Schematic drawing of quality-control phantom for measurements of regional cerebral blood flow by ^{133}Xe inhalation and washout method

tained with this phantom, which may be helpful in trouble-shooting.

rCBF PHANTOM DESCRIPTION

The phantom consists of a cylindrical chamber connected to a piston and pump assembly for simulating respiration (Figs. 1 and 2). The chamber has a volume of 2.5 l and is constructed of Lucite. The inside dimensions of this cylindrical chamber are 19 cm in diameter and 8.8 cm in length. A small cylinder with a piston and a stroke volume of 500 ml is connected to the bottom of the chamber. The piston is driven by a variable-speed pump.* An opening in the top of the chamber allows the chamber to be connected to the inhalation of rCBF rebreathing system. The phantom can simulate an entire rCBF inhalation study, including data analysis. The size of the chamber approximates that of a human head. This allows the external detectors to be positioned in a fashion similar to that used on the head of a patient. The volume of the chamber is approximately equal to that of the lungs. The operation of the piston assembly simulates respiration, and the stroke volume is approximately equal to the volume of gas inspired or expired during each respiratory cycle, that is, 500 ml. The stroke rate normally utilized is 8 strokes/min, which simulates resting breathing frequency.

A rapid and uniform distribution of ^{133}Xe and air in the chamber of the phantom is necessary to facilitate uniform measurements with the head detectors, which are positioned

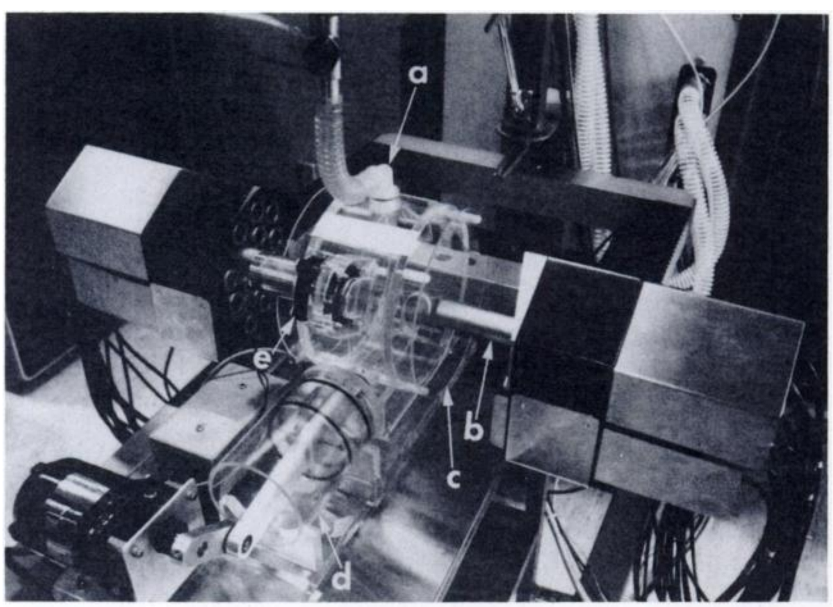

FIGURE 2
Quality-control phantom. Major parts are identified: a: Phantom ^{133}Xe administration system connection point; b: Head detector; c: Spacing plate on side of phantom; d: Piston and pump assembly; e: Blower motor

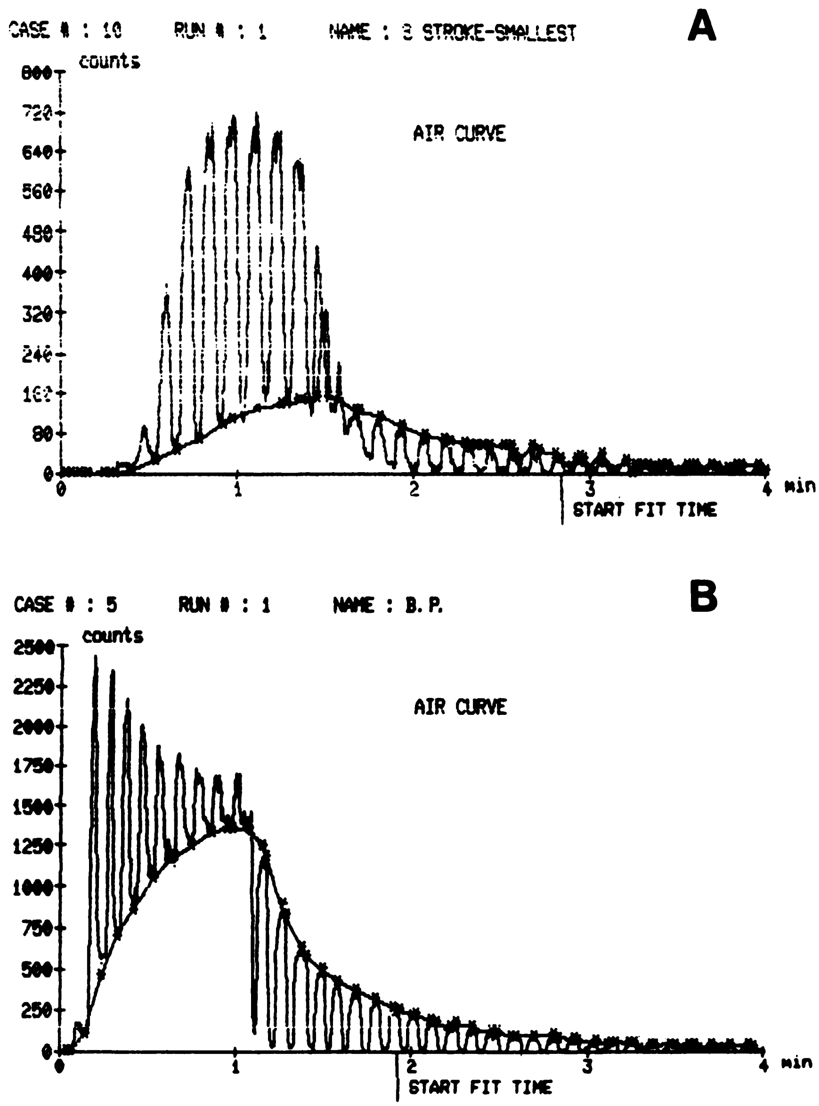

FIGURE 3
Air curve obtained with quality-control phantom (A) and from actual patient study (B). Note later peak and start fit time in phantom study, which is due to slower movement of air in phantom

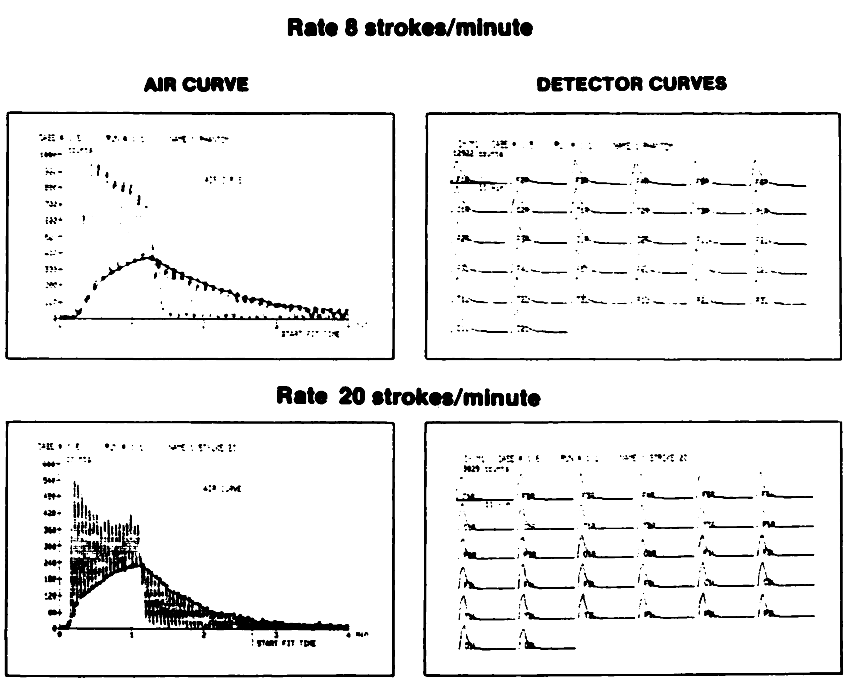

FIGURE 4
Air and detector curves obtained with different stroke rates of piston pump (respiratory rate). Note earlier peak and short fit time of higher stroke rate

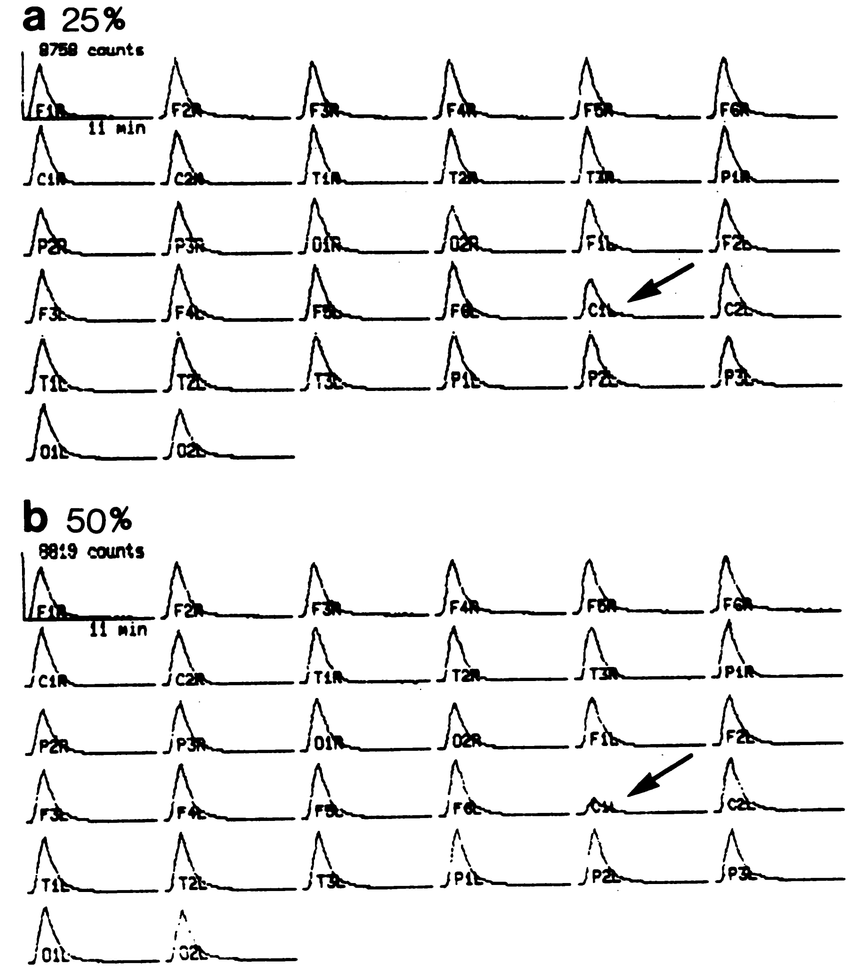

FIGURE 5
Low detector sensitivity (C1L), induced by detuning the given setting, shows little effect on washout curve for detector C1L if counts are reduced 25% from other detectors (a) but shows significant change when counts are reduced 50% (b)

at the outside of the chamber. Rapid mixing is enhanced by a blower motor with its baffle located within the chamber for increasing the gas recirculation. In addition, the orifice connecting the chamber to the instrument to be tested is only 2 mm in diameter, which increases the velocity of the gas flow between the chamber and the rebreathing unit of the rCBF system. This orifice size causes turbulence and increases the gas mixing within the chamber.

MEASUREMENT PROCEDURE

To prime the instrument for testing, ^{133}Xe is injected using a dispenser loaded with a vial containing a dose of ^{133}Xe. The priming is identical to that employed for routine patient studies. The amount of ^{133}Xe, however, is less than that used for patients, and ^{133}Xe ampules older than 1 wk can be used. With the air bag about three-fourths full of air, $\sim$5,000 counts per second should be registered on the air detector.

The air tube is then attached to the phantom in a fashion similar to that used in attaching the air tube to the patient's face mask. The external detectors are positioned at both sides of the chamber, with the collimators touching the surface. This also is similar to positioning the detectors on the side of the patient's skull.

The piston pump is then started with the xenon system still closed, just as would be done when the patient breathes using the face mask before the patient study. Next, the instrument is started, and the air and detector curves are immediately recorded.

After 1 min of ^{133}Xe delivery, the system automatically shuts off, and washout is determined from the air detector and the brain detectors when air only is ventilated.

In a properly functioning system, an air curve similar to that seen in patient studies is obtained and all detectors have identical-appearing washout curves on the image display. The computer-assisted data calculation routine, based on the two-compartment model, gives fast-flow values for each detector, a total mean flow, and the variation between the different detectors in terms of deviation from the mean flow.

RESULTS

Studies with this phantom were conducted with the chamber connected to the xenon administration system, as shown in Fig. 2. The air-sampling tube of the rCBF system has to be in the path of inspired and expired air in order to register the cyclic change of activity in the line during equilibrium and washout. If the sampling tube is positioned inside the chamber, an air-activity curve will not be generated. The detectors are pulled out to the spacing plates on either side of the chamber (Fig. 2). Before the study, all detectors are tuned

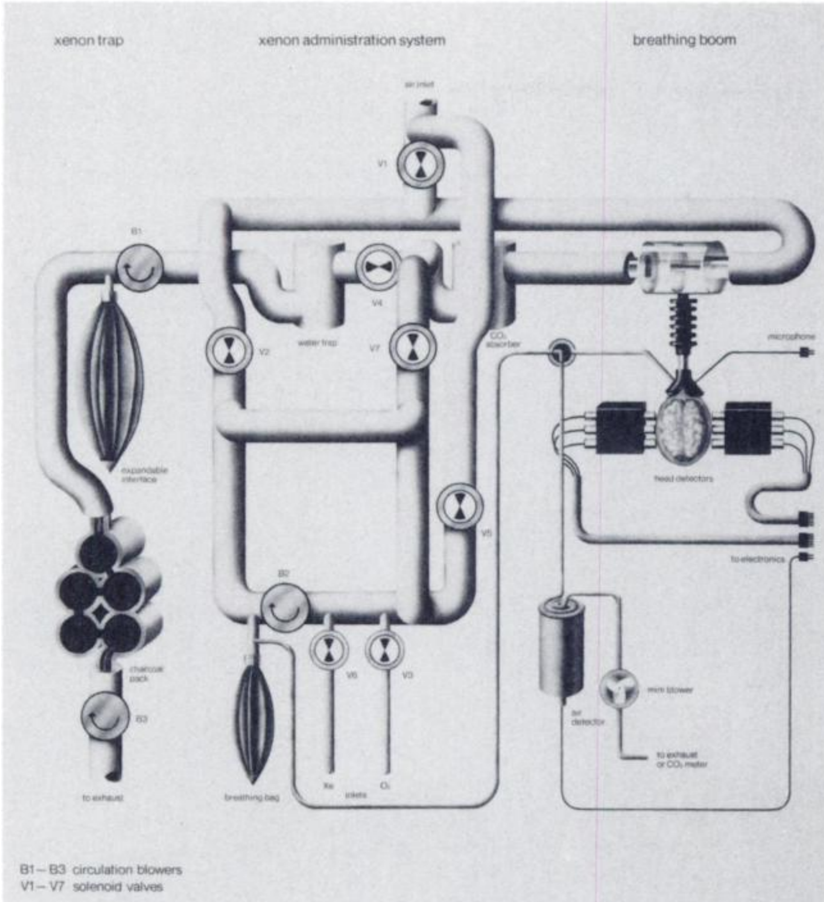

FIGURE 6
Schematic drawing of regional cerebral blood flow system used in this study. Valve and motor that were tested in this study are indicated. (From Novo Cerebrograph. By permission of Novo Diagnostic Systems A/S.)

individually to uniform sensitivity by means of a point source of barium-133.

A representative air curve obtained in the phantom study, shown in Figure 3A, is quite similar to the air-activity curve obtained in a patient study (Fig. 3B). The major difference is that the air curve in the phantom study is delayed relative to the patient curve. This delay is probably due to the less forceful pumping action of the phantom and the small orifice utilized to increase the turbulence. A phantom study requires about 4 to 5 mCi of ^{133}Xe and usually can be conducted with decayed xenon vials that cannot be used for patient studies.

A blower motor[†] mounted on the chamber assures adequate mixing of ^{133}Xe. The flow values for a phantom study calculated from the washout curves from the 32 detectors were uniform, with a coefficient of variation (CV) ranging from 1.3 to 2.8% for seven phantom studies. Without the blower motor the CV ranged from 3.6 to 6.1%. The variation in detector flow values increased because of incomplete mixing of ^{133}Xe with air in the phantom.

Another aid to increase the rate of mixing is the small orifice at the air inlet of the phantom. Changing the size of this orifice affected the uniformity of the detector response. Increasing the diameter of the orifice to 8 mm significantly increased the variation by a factor of 1.5 ($p = 0.05$). A 4-mm opening increased the variation by 1.4.

The pumping rate of the piston assembly was varied to study the effect on the air and head-detector curves. When the curves obtained at 8 and 20 strokes/min were compared, little difference was seen in the head-detector curves. The "respiratory" frequency increased as expected in the air curve at the higher stroke rate (Fig. 4).

INDUCED MALFUNCTIONS

The phantom was utilized to study the effects of a number of intentionally induced problems with the rCBF system's detectors, solenoid valve, vacuum pump, and circulation blower in the xenon administration system.

MALFUNCTIONING EXTERNAL DETECTOR

For proper operation, the gain of each external detector amplifier is adjusted so that the 81-keV peak of ^{133}Xe is set in a 50-keV symmetrical discriminator window. The gain of one detector was reduced such that the counts in the 81-keV peak decreased to 75% of peak counts. A phantom study demonstrated no significant effect due to the loss of counting efficiency (Fig. 5a). The resultant flow value of 168.9 ml/100 g/min and CV of 3.4% are within the normal range for phantom studies. This procedure was repeated with a detector detuned to 50% of peak counts (Fig. 5b). In this case, the detector uniformity showed a higher than normal CV (5%) while the detuned detector measured a flow value that was 15% below the mean; flow values from all other detectors were within

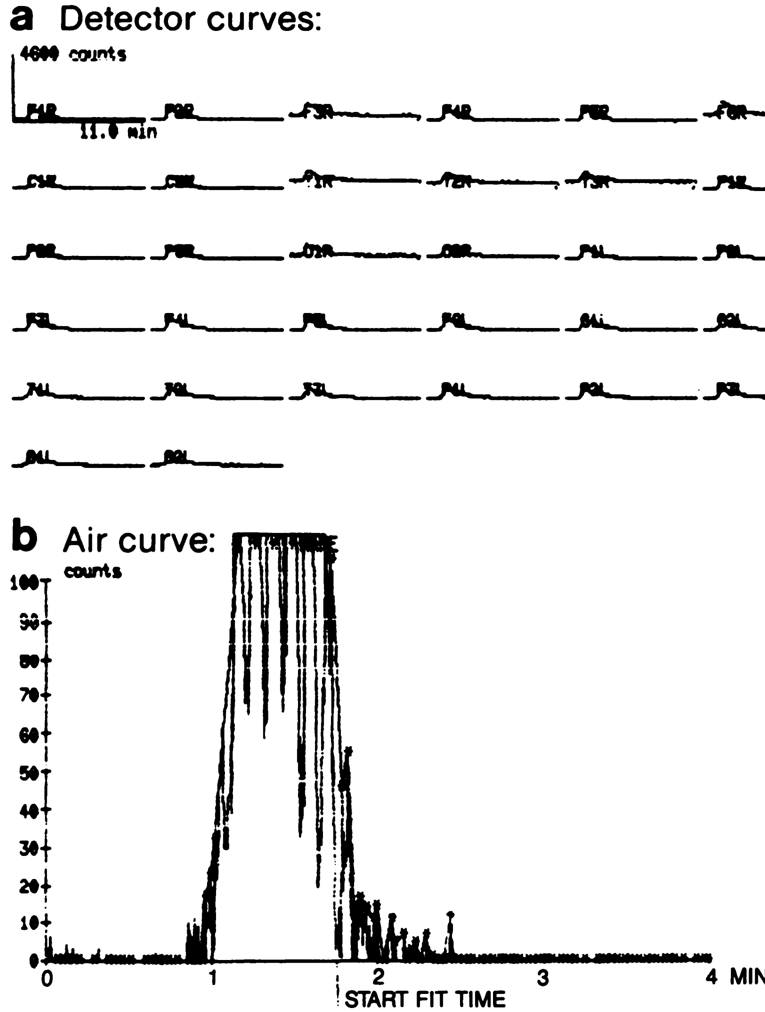

FIGURE 7
Detector (a) and air-curve (b) patterns when vacuum pump was disconnected

±10% of the mean. A detector was then set on the 30-keV peak of ^{133}Xe. In the resultant study, this detector was automatically excluded entirely from the calculation by the rCBF algorithm.

MALFUNCTIONING AIR SYSTEM VALVES

A number of faults were induced in the xenon administration system's solenoid valve and circulation blower. For location of these items in the instrument, see Fig. 6. Valve V1, which is normally closed during the equilibrium phase, was opened. The only effect on the phantom study was a significant decrease in the uniformity of the detector (CV 5.5%). A vacuum pump in the air-detector circuit was disconnected. Disconnection prevented almost all of the ^{133}Xe from reaching the phantom (Fig. 7). The average flow was 77.6 ml/100 g/min, a factor of 2 below the normal measured flow value in the phantom.

In a final trial, the circulation blower B2 was disconnected. This device ensures the mixing of ^{133}Xe and air in the breathing bag of the instrument. Disconnection resulted in very little ^{133}Xe being pumped to the phantom and the automatic exclusion of most detectors from the study (Fig. 8).

CONCLUSION

In summary, the rCBF phantom provides a means of testing and evaluating the operation of an rCBF inhalation system. Such testing is particularly important after a system malfunction or in maintenance. The use of the phantom could prevent unnecessary patient radiation exposure and improve the operating efficiency of the rCBF measurement laboratory.

FOOTNOTES

* Bodine Electric Co., Summerville, MA.
† Ripley SE 1507, Ripley Inc., Cromwell, CT.

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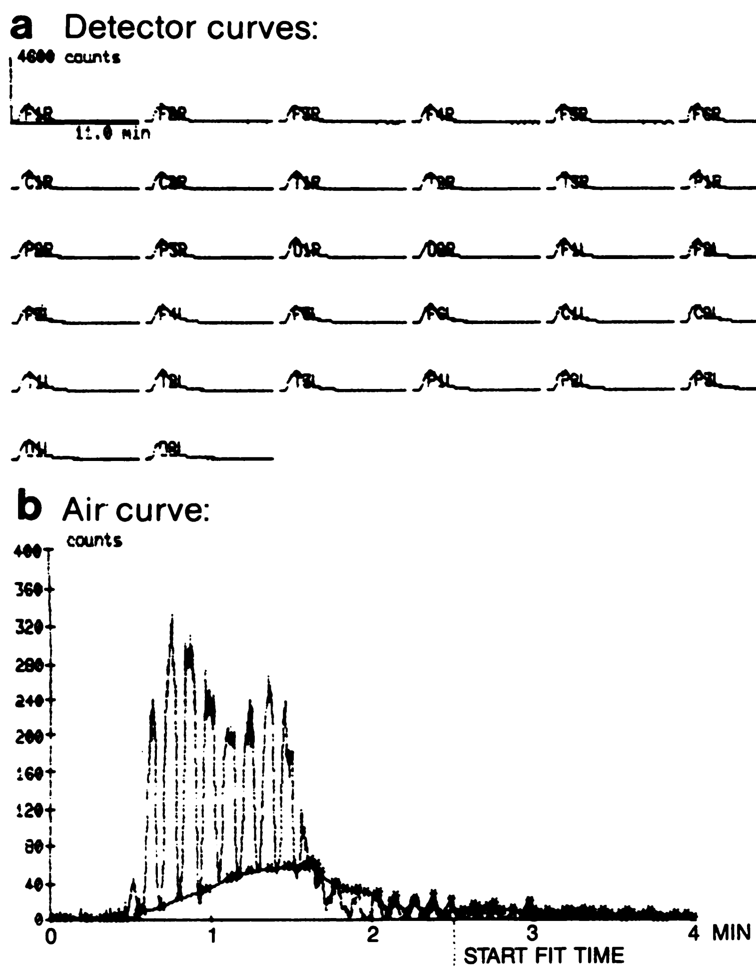

FIGURE 8
Detector (a) and air-curve (b) patterns with malfunction of circulation blower

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