A Dynamic Phantom for Radionuclide Cardiology

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A flow-based phantom has been developed to verify analysis routines most frequently employed in clinical radionuclide cardiology. Ejection-fraction studies by first-pass or equilibrium techniques are simulated, as well as assessment of shunts and cardiac output. This hydraulic phantom, with its valve-selectable dysfunctions, offers a greater role in training than in quality control, as originally intended.

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Noninvasive nuclear-medical procedures offer the cardiologist an atraumatic alternative to contrast angiography in the assessment of cardiac dynamic function. Image-based protocols have been developed that estimate ventricular ejection fractions, left-to-right shunts, and cardiac output. Invariably, a new diagnostic examination is judged in terms of its correlation with established diagnostic techniques. Such correlation is well-intended, but overlooks the more basic axiom that any technique, new or established, must be able to provide an accurate measure of the observed parameter under *known* conditions.

Examinations of the central circulation can be simulated by a sequence of hydraulic components that mimic the flow patterns through the great vessels, yet are conveniently separated for imaging. The fact that human anatomy is not so obliging in its organ placement does not detract from the usefulness of this dynamic phantom, which resolves the radioactive bolus in its passage through the mixing and contractile chambers. The phantom described below uncouples the problems of scintillation imaging from pump evaluation. Obviously the flow patterns through a patient are more complex than those found in this phantom (*1*), yet a simple fact stands out. If an analysis routine cannot deduce the ejection fraction of such a mechanical heart, cycling between accurately known end-points, it cannot be trusted in the more demanding clinical situation.

Description of the phantom. The phantom has characteristic volumes (heart-chamber, pulmonary, and systemic equivalents) that are variable over the physiologic range (*2*). The design criteria included the need to simulate the following procedures:

1. First-pass ejection-fraction studies.
2. Equilibrium multigated blood-pool imaging.
3. Left-to-right shunt quantitation.
4. Cardiac-output measurements.

All procedures allow the selection of either peripheral-venous injection or catheter administration of the radioactive bolus into

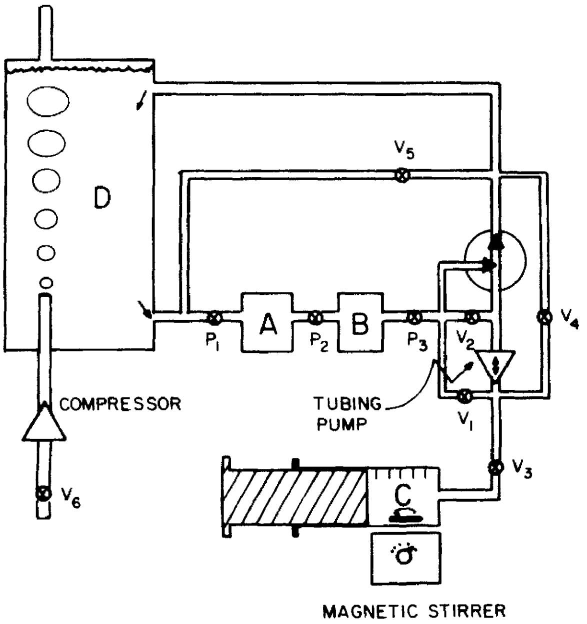

FIG. 1. Block diagram of dynamic phantom. Injection ports bracket right heart (A) and lungs (B) to simulate injection into a peripheral venous site (P_1), the pulmonary artery (P_2) or wedged into a pulmonary capillary (P_3). Tracer bolus is passively mixed in bead-filled volumes A and B, while left-ventricular (C) and systemic (D) volumes are actively mixed by magnetic stirrer and forced air. A reversible tubing pump drives the system, and circled check valves above pump act as mitral and aortic valves to ensure undirectional flow.

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TABLE 1. PHANTOM PARTS LIST

Component	Function	Supplier
Reversible tubing pump	Drives flow	Cole-Parmer No. 7545
Magnetic stirrer	Mixes LV contents	Cole-Parmer No. 4805
Compressor	Mixes systemic circ.	Cole-Parmer No. 7065
Double check valve	Mitral-aortic valve	Becton-Dickinson No. 3095
200-ml syringe	Left ventricle	Becton-Dickinson No. 2568
Valve 2	Mitral-valve leak	
Valve 4	Aortic-valve leak	
Valve 5	Left-to-right shunt	
Valve 6	Throttles mixing in systemic circulation	

Parts cost roughly $500, assembly time roughly 40 man-hours.

TABLE 2 PHANTOM OPERATING INSTRUCTIONS

STUDY	VALVE STATUS	PUMP STATUS	INJECTION	ROI
FIRST-PASS LEFT VENTRICULAR EJECTION FRACTION		↕	FLUSHED INTO P_1, P_2 OR P_3	LEFT VENTRICLE (C)
EQUILIBRIUM BLOOD-POOL IMAGING		↕	PREMIXED INTO TOTAL VOLUME	LEFT VENTRICLE (C)
LEFT-RIGHT SHUNT		↑	FLUSHED INTO P_1 (OR P_2 FOR $C^{15}O_2$)	LUNG (B)
CARDIAC OUTPUT		↑	FLUSHED INTO P_1, P_2 OR P_3	AORTA

VALVE LEGEND. ◀ CLOSED ◁ OPEN ⊲ OPEN TO SIMULATE SHUNT

the pulmonary artery (*3*) or a single pulmonary capillary (*4*). Furthermore, patency of both mitral and aortic valves can be independently compromised. Modular organization shown schematically in Fig. 1 assures that complex transpositions can be achieved by simple changes in tubing.

Practical considerations require that the phantom be operable as a routine quality-control exercise by technologists working in a clinical setting. For this reason, the phantom is self-contained, portable and is powered by 115 V ac. Flow patterns can be followed visually through the transparent tubing when a colored bolus is introduced. Table 1 lists the major components of the phantom, their function, and representative suppliers. Table 2 summarizes the phantom's operating instructions for the four procedures listed above. The status of the six valves is shown in the sectored hexagon, ordered clockwise as shown. Intermediate shading as shown in the legend indicates that opening the valve in question will simulate the pathologic shunt.

The contractile left ventricle consists of a 200-ml syringe, which is slaved to the reversible tubing pump. The sense-reversal switch on the pump controller edge-triggers a one-shot circuit to provide an artificial EKG gating signal for equilibrium-gated imaging studies.

RESULTS AND DISCUSSION

In Fig. 1 the right heart (A), lung (B), left ventricle (C), and systemic circulation (D) are clearly resolved in the dynamically acquired images, and are outlined respectively as regions of interest. Figure 2 shows the left-ventricular (C) activity curves following the sequence of pulmonary-wedge, pulmonary-artery (Swan-Ganz), and peripheral-vein injections into the phantom cycling between end points of 75 and 150 ml. Application of a commercial analysis routine to the first ten beats of these three data sets resulted in ejection-fraction estimates of 0.47, 0.47, and 0.44, respectively. Similar tests over the physiologic range of ejection fractions are faithfully analyzed by the image-based, first-pass routine.

This good agreement is less than remarkable in view of the complete absence of interference from nonventricular activity. The more realistic clinical situation is simulated by intentionally enlarging the left-ventricular region of interest (C) to incorporate neighboring structures. Here the didactic potential of the phantom becomes evident. In one exercise, left-ventricular activity can be purposely contaminated with pulmonary and left-atrial contributions (B), but background-corrected as though the nonventricular events were coming from the systemic circulation (D). The lagged time dependence of the ill-chosen background causes the computed ejection fraction to increase predictably in the later beats. With practice, the data analyst learns to associate such characteristic LVEF instabilities with their cause, namely a background mismatch. The next step in the learning program is to repeat the first-pass exercises with progressive opening of valves 2, 4, and 5 to stimulate valvular insufficiencies and shunts.

The remaining maneuvers listed in Table 2 adequately exercise the system's software through gated blood-pool analysis and the quantitation of cardiac shunts and output. These routines are less demanding in that they derive the desired parameter from a smaller frequency set out of the cardiac activity curve. As an example, total ventricular ejection fraction is frequently deduced by multigated imaging of Tc-99m HSA in the great vessels at equilibrium. However, without the insight revealed by the initial

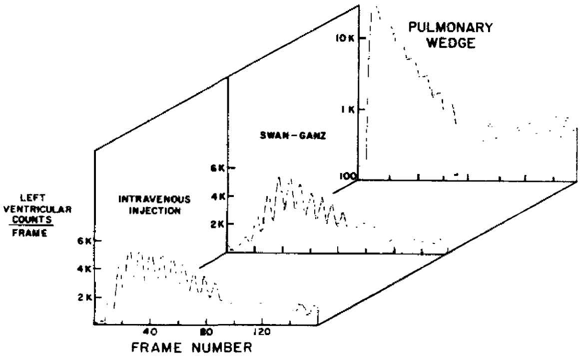

FIG. 2. Three first-pass ejection-fraction studies, differing only in injection site. Curves denote left-ventricular activity following flushed injection of pertechnetate bolus into ports P_1, P_2, and P_3, respectively. Pulmonary-wedge (P_3) study requires a logarithmic ordinate; other two are linear.

bolus propagation, the difficulty of background quantification is reminiscent of the offset problem that plagues any measurement of an ac signal superimposed on a dc component.

CONCLUSION

A dynamic phantom has been constructed to mimic the central circulation for quality control and training in scintigraphic cardiology. The desire to simulate a wide variety of cardiac procedures has suggested a fluid-based device rather than a "dry," eclipsing alternative (*5*) suited for gated equilibrium image evaluation. This versatility has led to the verification of commercial analysis routines for the assessment of ejection fractions, shunts, and cardiac output.

Our concept of the utility of this phantom has evolved during our initial experience with it. Exposed plumbing needed for effective teaching tends to intimidate technologists responsible for day-to-day quality-control evaluation. Furthermore, it is clear that the effectiveness of this phantom as a teaching tool lies not in data acquisition but in the dynamic studies themselves that are generated. Rather than starring in a hydraulic road-show at each nuclear medicine laboratory, the phantom could be more effectively used to generate parent data sets that could be disseminated by magnetic-disc or tape exchange. The clinician responsible for cardiac analysis could then pace himself through a graded series of increasingly complex evaluations. Correct responses would be anticipated, yet access to the original image data would allow the student to pursue his own line of questioning while learning to follow the tracer bolus through a realistic maze.

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