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Flow Analysis with Digital Subtraction Angiography:

1. Description of a Simplified Flow Model

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An inexpensive, simplified flow model for use with digital subtraction angiographic (DSA) equipment is described. System tests show that the model gives reproducible data with a standard deviation of ±2.6%. Flow analysis also reveals an appropriate response to flow rates of 20–240 ml per min. The flow model can be used to investigate many of the variables and sources of error in DSA flow measurements.

The ability to measure blood flow and regional circulation to the brain is of considerable importance in clinical practice. In cases of cerebral vascular disease, regional circulatory changes may indicate whether a stenosis is hemodynamically significant. Sequential filling of arteries on an angiogram has long been used for that purpose [1]. In addition, many techniques have been developed specifically to make that determination, including multiple noninvasive tests [2], radionuclide flow studies [3], and dynamic computed tomography (CT) [4]. Quantification of cerebral blood flow may help determine the adequacy of collateral circulation and perfusion to ischemic areas of the brain. Xenon cerebral blood-flow studies [5], xenon-transmission CT [6], and positron-emission tomography [7] are proven methods for quantifying regional cerebral blood flow.

Lantz and his coworkers [8] developed a video densitometric method that measures flow within an artery as a fraction of the cardiac output and gives a relative flow measurement. If the cardiac output is known, the actual flow can be calculated. They successfully applied this method to evaluate carotid and renal stenoses [9–11].

The development of digital subtraction angiography (DSA) provides an additional method to evaluate carotid and cerebral blood flow quantitatively. DSA flow analysis is also a videodensitometric technique. The accuracy and reliability of DSA systems for quantifying cerebral blood flow remain to be determined. The time-density (T-D) curves produced by the DSA technique are affected by many variables and sources of error, including flow, vessel size, iodine content, subject density, misregistration, background noise, X-ray scatter, and veiling glare. Because these variables are difficult to control in clinical practice, we developed a flow model for our DSA system.

Description of the System

Flow Model

A DSA flow model was constructed from existing equipment and supplies already available in any radiology department. It is an open-ended system made with extension tubing (K50, Pharmaseal, Tao Alta, PR) and adult pressure-monitoring line (NAMIC, Hudson Falls, NY) (Fig. 1). A 5-French dilator is inserted through a plastic side-angle fitting (Cook, Bloomington, IN) into a barrel connector, which serves as an injection reservoir. The dilator has two side holes and no end hole for

better mixing. The system is taped to a 1-in.-thick (2.5 cm) aluminum block, which provides some subject density.

The flow in the system is provided by a Med-Rad Mark IV injector with a 130-ml syringe. The contrast medium is injected with a Med-Rad Mark III injector adapted for a 2-ml syringe to provide accurate injections of small volumes (Fig. 2). Three-way plastic stopcocks (Cook, Bloomington, IN) permit easy refilling of the injectors with water and contrast material. Any available containers can be used for water and waste reservoirs.

Technical Factors

The flow model is positioned midway between the X-ray tube and the image intensifier, giving a magnification factor of 2. Standard radiographic techniques are 70 kVp, 200 mA, and 0.024 sec, with the small focal spot (0.3 mm). Flow studies are performed by using the model with a Technicare DR 960 digital angiographic system (Technicare Corp., Solon, OH) with a 4-in. (10-cm) mode on the image intensifier, a 256 × 256 matrix, and a framing rate of 4 per sec for a total of 10 sec per run. Standard system flow is 59 ml per min. The

contrast injection is delayed 1.5 sec and consists of 0.35 ml of Hypaque (Winthrop, New York, NY) injected over 1 sec.

Flow Curves

Flow analysis is done by using the available software programs of the Technicare Digital System. To generate T-D curves, we place regions of interest (ROI) over the areas to be measured. After a mask frame is selected, the computer calculates the density (DR numbers) of the pixels within each ROI for each frame of the run. The data are displayed as a graph with the frame number along the abscissa and the density along the ordinate (Fig. 3B). There are additional software programs for flow-curve analysis, including (1) subtracting one curve from another, (2) scaling a curve to make it larger or smaller, (3) fitting a curve to the flow data (linear, exponential, gamma variate), and (4) integrating the area under the curve.

System Evaluation

Background Noise

The flow model and DSA system were first tested for background noise relative to the density of the contrast media
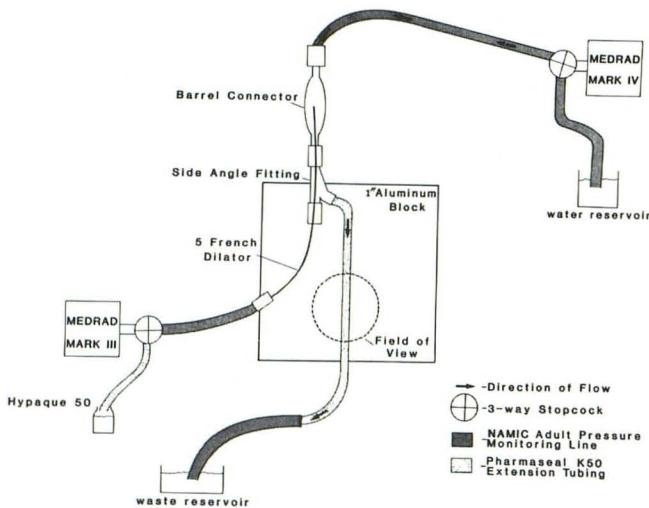

Fig. 1.—DSA flow model. System flow is provided by Med-Rad Mark IV injector, and contrast material is injected with Med-Rad Mark III injector.
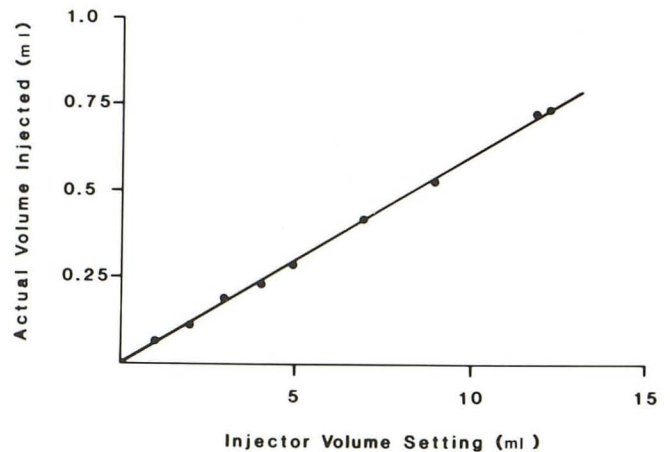

Fig. 2.—Med-Rad III injector adapted for 2-ml syringe. Actual volume injected is approximately 1/20 of volume setting.
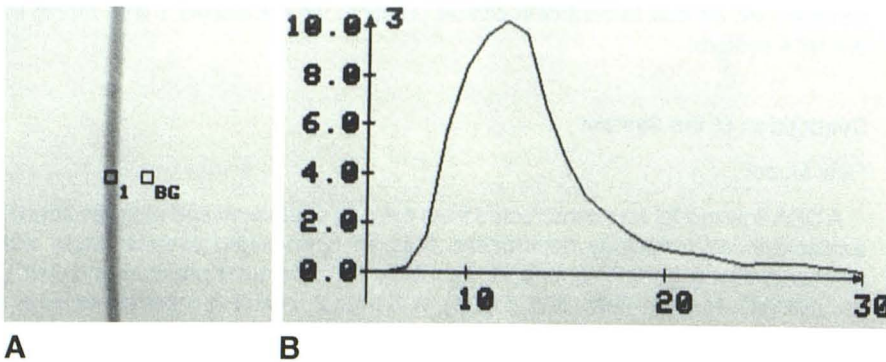

A   B

Fig. 3.—Generation of T-D curve. **A,** Regions of interest are placed on tube (1) and background (BG). **B,** Background values are subtracted from tube density to give final T-D curve.

in the tube of the model. The ROIs were placed over the tube and the background (Fig. 3A). The background density ranged from +6% to −6% of the peak contrast density. The background density was subtracted from the contrast density for each frame of a run; the resulting density numbers were used to generate the final T-D curve (Fig. 3B).

Reproducibility

The reproducibility of the system was tested by performing 10 DSA runs with identical standard technique. For each run, ROI boxes were placed over three adjacent areas of the model vessel and another ROI was placed on a background region. Flow curves were generated by using averaged data and subtracting the background from each of the three contrast areas. The integrated areas under the curves were calculated and an average of three values was obtained. The mean value of the integrated area for the 10 runs was 67.5 with a standard deviation of 1.8 (% SD = 2.6).
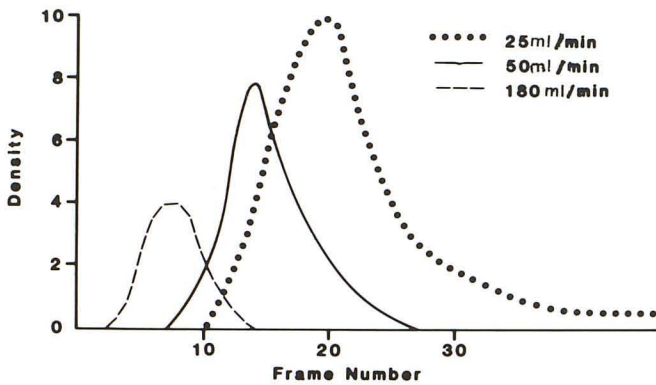
Response to Different Flow Rates

The DSA flow model was next tested for its response to changes in flow. The flow rate was varied from 20 to 240 ml per min, with all other variables constant. T-D curves were generated for each flow rate (as described in the *Reproducibility* section). As the flow rate increased, the curves appeared earlier along the abscissa and the curves were smaller (Fig. 4). The integral was obtained for each curve and plotted as a function of the flow rate (Fig. 5A). The area under the curve was an inverse exponential function of the flow rate. When the flow rates were plotted as reciprocal functions, a linear relationship was observed (Fig. 5B).

Discussion

An inexpensive DSA flow model was devised from materials that are readily available in any radiology department (Fig. 1). A constant flow rate was used for simplicity. Although pulsatile flow more accurately reflects an in vivo situation, it is also more complex and requires elastic tubes and arterial pressure and resistance.

Many changes were made in our model during its development to optimize the flow curves. Initially, the model was positioned horizontally, but layering of contrast material was a major problem. With any layering or stagnation of flow, the contrast material remains within the field of view longer, resulting in falsely high density numbers and an increased integrated area under the curve. This problem was largely eliminated by placing the model in a vertical position and filming with a horizontal beam. Layering will be a problem with flow measurements in clinical situations. Even with the vertical position, streaming to one side of the tube and stagnation of the contrast material along the inner wall of the tube occurred, although this was less of a factor with higher flow rates. Since the maximum capacity of the syringe used in the Mark IV injector is 130 ml, lower flow rates are preferable as long as they are high enough to avoid streaming.

When an end-hole catheter was used for the injection of

Fig. 4.—As flow rate increases, T-D curves become progressively smaller and appear earlier along abscissa.

Fig. 5.—Response of DSA flow model to different flow rates. **A**, Area under the T-D curves decreases exponentially as flow rate increases. **B**, Plotting reciprocals of flow values results in linear relationship.

A

B
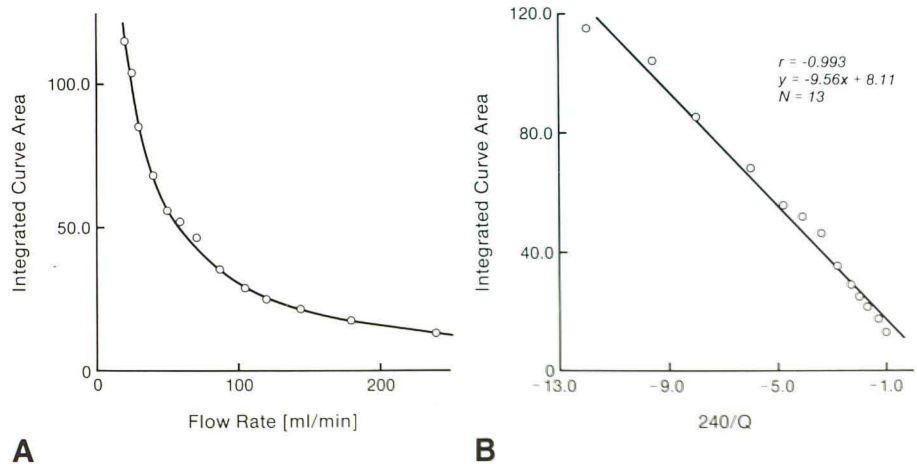
the contrast material, invariably streaming occurred consistently, whether the catheter was directed downstream or upstream. Consequently, the end hole was occluded and two side holes were made. With this catheter, the injection resulted in jetting of the contrast material downstream into the field of view. This was corrected by inserting the barrel connector as an injection reservoir. In addition, there was better mixing of the contrast material in the system.

Initial tests with the Mark III injector showed that the actual output varied as much as 20% at low-volume settings. Therefore, the injector was adapted for a 2-ml syringe, which gave a scaling factor of approximately 0.05. For the standard technique, the injector was set at 6 ml to deliver approximately 0.35 ml of the contrast material (Fig. 2). This volume was selected to provide density measurements similar to those obtained in a clinical setting. For accurate flow measurements, the injection rate must be less than 50% of the system flow rate [8]. Hypaque 50 was selected as the contrast agent because of its relatively high iodine content (300 mg/ml) and low viscosity (3.25 cps at 25°C). Other contrast agents were not tested with the model.

DSA systems are inherently noisy. Noise can enter anywhere along the imaging chain, such as at the image intensifier, TV camera, or analog-digital (A-D) converter. The noise introduces error into the density measurements and flow curves (see *System Evaluation* section). Background subtraction reduces this error but does not eliminate it since system noise is random and of varying intensity throughout the field of view.

Since the video signal is logarithmically amplified in DSA systems density measurements are directly proportional to the thickness and concentration of contrast material. The values assigned to density measurements are relative and do not have the same significance as CT numbers. They vary from case to case depending on the technical factors used. Nevertheless, our results show that if successive runs are done with all the factors constant, reproducible flow curves can be obtained.

The integrated curve area is inversely related to the flow. It has also been shown that the curve area is directly related to the cross-sectional area of the vessel and the total amount of iodine injected [8]. This can be expressed in a formula as follows: $A_c = (A_v I/Q) (k)$, where A_c = integrated curve area, A_v = cross-sectional area of the vessel, I = amount of iodine, Q = flow, and k is a constant. The constant incorporates all of the variables that affect T-D curves, such as radiographic technique, gain of the image intensifier and video system, log amp function of the DSA system, frame rate, and specific methods for generating and integrating the T-D curves. This constant can be determined by testing the flow model with known flow values. Once k is determined, the equation can be solved for Q and absolute flow values can be determined from the integrated curve area on subsequent DSA runs, if the vessel size and amount of iodine injected are known and if the other variables are kept constant. The effect of operator-controlled variables on the T-D curves is described in our companion article [12], which also discusses the accuracy of DSA flow measurements.

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