A Computerized Technique for the Display and Comparison of Regional Cerebral Blood Flow Data

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SUMMARY A technique is described by which the size, shape and orientation of the brain with respect to detector positioning can be reproduced by computerized simulation. Head size is estimated from the distance between the external acoustic meatus (EAM) and the outer canthus and head shape is determined from the length and height of the skull. These values are used to magnify and alter the shape of a standard brain outline to comply with individual patient measurements. The location of the EAM and nasion are used to establish the displacement and rotation of the orbito-meatal base line with respect to the detector holding assembly. The corrected brain outline is then rotated, centered and displayed superimposed on the regional flow data. Comparison of flow data from 2 studies is accomplished by mapping each probe location onto the standard brain and projecting these brain coordinates onto the second study. Flow data from the nearest detectors are averaged to obtain the interpolated flow value for that brain region. This method corrects for differences in head size and shape between patients and for changes in head positioning and rotation between studies. Computer simulation studies demonstrated that this correction procedure can significantly reduce the variance of flow measurements for expected ranges of head size and orientation.

MANY CENTERS are now using multi-detector systems for the measurement of cerebral blood flow (CBF) following injection1-2 or inhalation3,4 of 133Xenon. The principle advantage of multi-detector systems is that they allow the simultaneous determination of regional CBF in many areas of the brain, thus producing a map of the distribution of flow rates over the cerebral hemispheres. CBF varies substantially from one area of the brain to another. Flow variations of 10-15% between adjacent detectors are not uncommon under resting conditions in normal man5-7 and larger differences are to be expected during activation procedures or in patients with cerebrovascular disease.1,4 Therefore, it is important that the information obtained from each detector is related accurately to the position on the brain from which the clearance curve was obtained.

The purpose of this communication is to describe a technique by which the size, shape and orientation of the brain with respect to detector positioning can be reproduced for display by computerized simulation. The method corrects for alterations in head positioning between studies and for differences in head size and shape between patients. This allows direct comparisons of flow results from 2 or more studies based on the anatomical location of the detectors during data accumulation. The effects of alterations in detector positioning on the reproducibility of repeated CBF measurements will also be described.

Methods

The equipment used for CBF measurement is a 32-channel system (Novo Diagnostic Systems) with parallel array detector positioning. The detector holding assembly consists of 2 lead-shielded blocks mounted opposite each other such that opposing pairs of detectors are coaxial. Each block contains 19 detector locations and, in addition, up to 4 detectors can be positioned over the vertex of the skull making a total of 23 possible detector locations on each side of the head. Data storage, analysis and display calculations are done on a PDP 11/60 computer (Digital Equipment) and displayed on a graphics terminal (Tektronix, Model 4010-1).

At the beginning of each study, one of a set of standard detector placement patterns are selected and displayed. Any alterations in probe positioning for the current study are made by entering the detector number (1-32) and the new location number (1-46). The corrected detector locations are then stored with the rest of the study parameters (blood pressure, Pco2, etc.). In subsequent display or comparison procedures, information pertaining to a particular detector (clearance curve, flow index, etc.) is displayed at the corresponding location within the detector block. This allows complete flexibility of probe positioning from one patient to the next.

Projection of the Brain Outline

A set of idealized outlines of the skull and brain were drawn based on average head size and shape as reported by Lang et al.8 The outlines and reference measurements are shown in figure 1. The polar coordinates required to reproduce these outlines were calculated with the external acoustic meatus (EAM) as the center for all radial measurements and the orbito-meatal base line (OMBL) aligned at zero degrees.

Magnification and Correction for Head Shape

For each patient, the distance from the center of the EAM to the outer canthus and the length and height of the skull are measured as indicated in figure 1. The measured distance from the EAM to the outer canthus is divided by the corresponding distance on the
standard skull outline. This provides a magnification factor relating the standard outlines to the patient's head size. This magnification factor is first applied to the measurements from the standard outline to determine a calculated length and height for the patient's skull. If the calculated values both agree with the measured distances to within ± 5 mm, no correction for differences in head shape is necessary. The radial coordinates of the standard brain outline are simply multiplied by the magnification factor and one proceeds directly to the centering and rotation procedures.

To correct for head shape, the standard brain outline is converted from polar coordinates \((r, \theta)\) to rectangular coordinates \((X, Y)\). All distances measured parallel to the orbito-meatal base line \((X\text{-axis})\) are multiplied by the ratio of the measured length of the skull to the standard length. Similarly, all distances measured perpendicular to the orbito-meatal base line \((Y\text{-axis})\) are multiplied by the measured skull height/standard height. This process alters the shape of the standard brain outline and magnifies the corrected outline to the proper size. The corrected rectangular coordinates are then converted back to polar coordinates. Mathematically, this procedure can be summarized in 2 equations: one for the radial correction and one for the angular correction as follows:

\[
\begin{align*}
rc &= r_s \sqrt{\left(\frac{H_m}{H_s}\right)^2 \cdot (\sin \theta_s)^2 + \left(\frac{L_m}{L_s}\right)^2 \cdot (\cos \theta_s)^2} \\
\theta_c &= \tan^{-1}\left(\frac{H_m}{H_s} \cdot \frac{L_s}{L_m} \cdot \tan \theta_s\right)
\end{align*}
\]

where \(r_s\), \(\theta_s\), and \(r_c\), \(\theta_c\) are the standard and corrected polar coordinates and \(L_s\), \(H_s\) and \(L_m\), \(H_m\) are the standard and measured skull length and height. If \(H_m/H_s\) equals \(L_m/L_s\), the conversion reduces to:

\[
\begin{align*}
rc &= r_s \cdot \frac{H_m}{H_s} \\
\theta_c &= \theta_s
\end{align*}
\]

which corresponds to a simple magnification of the radial coordinates as described above.

**Rotation and Positioning of the Brain Outline**

At the beginning of each study, an acetate sheet lined with a 1 mm grid is attached to the detectors in each probe block and advanced as close as possible to the patient's head. The position of the EAM on one side is then compared to that on the opposite side and, if necessary, the head position is modified such that the coordinates are the same. This procedure ensures that the head is perpendicular to the plane of the detectors. The X-Y coordinates of the EAM and the nasion are then stored with the study information. The angle of rotation of the OMBL with respect to the detector block is calculated using the coordinates of the EAM and nasion and this rotation angle is added to \(\theta_c\) of the corrected brain outline. The final step in the display procedure is to center the EAM of the corrected outline on the measured coordinates and then draw the brain outline superimposed on the detector data display. The entire process is summarized in figure 2.

**Comparison Techniques**

**Comparison of 2 Studies (fig. 3)**

Each detector location is checked against the detector positioning data from study #1. When an occupied location is found, the central coordinates of that location are mapped onto the standard brain outline by performing the calculations described above in reverse order. This process defines the location on the brain from which the flow value in study #1 was obtained. These brain coordinates are then projected onto the second study using the appropriate head size and positioning data. All occupied detector locations from study #2 within one probe diameter (28.5 mm) of the calculated brain coordinates are then examined. If a detector is found to be within 5 mm of the calculated position, the flow value from that detector is used for comparison. If there are no detectors within 5 mm, then the flow values from the neighboring detectors are multiplied by the fractional distance from the center of the detector to the calculated brain coordinates to obtain an interpolated flow value for that brain location. Finally, the requested comparison (mean value, absolute or percent change in flow, etc.)
is made between the flow value from study #1 and the interpolated flow value corresponding to that brain location in study #2.

Multiple Study Averaging

To average the results obtained from a series of flow studies, the standard brain outline is partitioned into regions of an appropriate size (1 cm × 1 cm, 2 cm × 2 cm, etc.) and the center of each preselected region is then treated as a calculated brain coordinate. These coordinates are projected onto each study in the series and the flow value corresponding to that brain location is calculated as described above. Mean values and statistical data are compiled for each region. A similar process is used to determine the average response to a particular stimulus (hand movement, psychological testing, etc.). Individual responses from paired studies (control-test) are calculated using the methods described for comparison of two studies. This produces a map of the response data for that patient. The preselected coordinates from the standard brain are then projected onto this map and the response in each brain location is calculated.

Computer Simulations

To test the effects of alterations in detector positioning or variations in head size on regional CBF measurements, a phantom was generated using...
regional CBF data available in the literature.1-8. A 1 cm X 1 cm grid was positioned on the standard brain outline and flow data were entered manually to correspond to normal resting CBF values in each brain region. Head positioning and rotation coordinates were then chosen such that the detectors were centrally located on the brain phantom and a CBF value was calculated for each detector by averaging the flow data within 15 mm (one detector radius) of the center of that brain location on the phantom.

The vertical positioning of the nasion with respect to the detectors was then altered by ±15 mm corresponding to an 8.5° "head up" or "head down" rotation when compared to the control orientation. Head size and the location of the EAM remained constant. This moved the detectors on the phantom and the resulting CBF patterns were calculated. The CBF values obtained at each detector location were converted to a percentage of the control mean hemispheric flow and the changes in CBF were then calculated both before and after correction for head movement. In subsequent simulations, the position of the EAM was altered by ± 10 mm (keeping head size and rotation constant) and head size was altered by ± 10% (keeping EAM positioning and rotation constant). Flow maps were generated for each new orientation of the detectors on the brain phantom and the changes in flow were assessed as described above.

Results

It should be emphasized that the true CBF pattern did not change from one simulation to the next and therefore all apparent "changes" in flow are the result of detector movement from one brain region to another. The results of the simulation studies are summarized in the table.

Failure to correct for alterations in probe orientation relative to the brain resulted in apparent changes in CBF of up to 10% in an individual detector. Mean hemispheric CBF was not affected significantly. However, the variance of repeated measurement was quite large, ranging from 3.7 to 14.4%. Following correction for probe orientation, the maximum apparent change in CBF was 3% for an individual detector and the variance was reduced to between 0.7 and 2.0%.

Larger movements of the detectors with respect to the brain tend to shift one detector onto a position occupied by another detector in the previous study. This would create large errors if uncorrected for head positioning but should reduce the errors once corrected for positioning. This situation was tested by repositioning the detectors on the brain phantom and examining the effects of a 30 mm change in detector orientation. As expected, apparent changes in flow of up to 12% were observed with a variance of 15.3%. Following correction for detector positioning, the maximum apparent change in flow was 1% with a variance of 0.3%.

Discussion

Several techniques have been developed to relate detector positioning to either extracranial or cerebral landmarks. One approach has been to mark the center of several probes with lead and record their position radiographically.9,10 The main advantage of this method is a high degree of accuracy in demonstrating the positioning of the detectors with respect to the brain. However, this involves additional radiation exposure for the patient and is somewhat impractical for routine reporting of CBF results because of the large number of studies now done using non-invasive techniques. The method also makes comparisons between studies very difficult since the results must be transposed onto a single diagram and then analyzed by brain region.9 Another technique has been to orient the detectors with respect to extracerebral landmarks in a standardized fashion.4,8 The flow results are then displayed on a standard map of the brain with fixed head size and probe orientation. Since there is considerable variation in head size and shape between patients, the method is not very accurate in demonstrating the true positioning of the detectors on the brain. In addition, averaged data obtained from a group of patients will be influenced by this inaccuracy.

Table 1. Apparent Percentage Change in CBF Before (B) and After (A) Correction for Alterations in Detector Orientation with Respect to the Brain

<table>
<thead>
<tr>
<th>Change in Orientation</th>
<th>Range</th>
<th>Percentage Change in CBF*</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1 Run 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rotation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control 8.5° Head Down</td>
<td>-3 to +6</td>
<td>-1 to +1</td>
<td>0.5</td>
</tr>
<tr>
<td>Control 8.5° Head Up</td>
<td>-4 to +3</td>
<td>-2 to +2</td>
<td>-0.3</td>
</tr>
<tr>
<td>Head Up Head Down</td>
<td>-10 to +6</td>
<td>-2 to +2</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Lateral Positioning</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control 10 mm Anterior</td>
<td>-3 to +5</td>
<td>-2 to +2</td>
<td>0.9</td>
</tr>
<tr>
<td>Control 10 mm Posterior</td>
<td>-5 to +3</td>
<td>-2 to +1</td>
<td>-0.5</td>
</tr>
<tr>
<td>Posterior Anterior</td>
<td>-5 to +6</td>
<td>-2 to +3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Head Size</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control 10% Reduction</td>
<td>-2 to +4</td>
<td>-1 to +2</td>
<td>0.8</td>
</tr>
<tr>
<td>Control 10% Increase</td>
<td>-4 to +1</td>
<td>-2 to +1</td>
<td>-0.6</td>
</tr>
<tr>
<td>Increase Reduction</td>
<td>-3 to +5</td>
<td>-2 to +3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*The change in CBF was calculated for each of 16 detectors (run 2 — run 1) and is expressed as a percentage of the control mean hemispheric flow.
since the recording site will vary from one patient to the next. This will have the effect of smoothing out regional CBF differences and increasing the variance of the measurement as demonstrated by the computer simulation studies. This problem has been largely overcome through the use of a helmet montage in which the detectors are situated radially rather than in a parallel array. This arrangement will minimize alterations in probe positioning due to varying head size but will only partially compensate for differences in head shape. Another possible disadvantage of standardized probe placement patterns is that the detectors cannot be rearranged to concentrate on a specific region of clinical interest.

The present technique represents a different approach to the problem of detector localization and is suitable for parallel array detector systems. The size, shape, rotation, and lateral positioning of the brain are accurately reproduced based on measurements obtained from each patient. The method does not require a standard probe placement pattern and allows complete flexibility in the positioning of the detectors within the detector holding blocks. The results of the simulation studies demonstrate the importance of comparing CBF data based on the anatomical positioning of the detectors. The variance of repeated CBF measurements can be expected to increase by approximately 4% for small movements (±10 mm), 8–10% for larger movements (±20 mm) and by 15% when adjacent detectors are superimposed (±30 mm). Variations in head size between patients produced apparent changes in CBF equivalent to those resulting from inaccurate repositioning. When the same data were compared using the methods described above, the variance of repeated measurement was reduced to 2% or less. Therefore, the technique retains the accuracy and detector positioning flexibility of the radiographic method and also corrects for alterations in head size and shape — a feature inherent in the radial arrangement of the helmet montage. It is anticipated that this will significantly improve the reproducibility of CBF measurements obtained using parallel array detector systems and will facilitate the calculation of average CBF patterns and responses from multiple patient studies.

References
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