Systems analysis of cerebrovascular pressure transmission: an observational study in head-injured patients

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In an observational study in head-injured patients, cerebrovascular pressure transmission was investigated using a systems analysis approach whereby the blood pressure (BP) waveform was used as a measure of an input stimulus to the cerebrovascular bed (CVB) and the intracranial pressure (ICP) waveform as the response to that stimulus. The transfer function is a measure of how much pressure is transmitted through the CVB at a given frequency and is calculated using Fourier analysis of the pressure waveforms. The transfer function allows quantification of the pressure transmission performance of the CVB, thus providing a basis for comparison between normal and abnormal function.

Fifteen hundred samples of ICP and BP waveforms were collected from 30 head-injured patients via microcomputer. Off-line spectral analysis of the waveform database revealed four main classes of transfer function: those with an overall flat transfer function (curve type 1); those with an elevated low-frequency response (curve type 2); those with an elevated high-frequency response (curve type 3); and those exhibiting both an elevated low- and high-frequency response (curve type 4). Curve types 2 and 4 were most often associated with raised ICP (> 20 mm Hg), whereas curve types 1 and 3 were most often affiliated with ICP less than 15 mm Hg. Studies of this type may provide insight into the pathophysiology of the CVB and ultimately aid in the prediction and treatment of raised ICP.

KEY WORDS • intracranial pressure • head injury • blood pressure • systems analysis • cerebrovascular bed • waveform analysis

THE intracranial pressure (ICP) waveform is increasingly being studied as a means of gaining insight into vascular factors affecting ICP.2-4,7,11,16,19,26 Portnoy and coworkers5,18-21 were the first to apply spectral analysis of the blood pressure (BP) and ICP waveforms in a systems analysis approach to the study of pressure transmission across the cerebrovascular bed (CVB) in experimental models of raised ICP. We have adopted their methods and applied them to a study of pressure transmission across the CVB in head-injured patients.

The aim of this study was to determine whether these methods can detect, in the head-injured population, any pressure transmission characteristics of the CVB associated with raised ICP. At the same time, the inherent variability of cerebrovascular pressure transmission in head-injured patients could also be defined. The methods and results of an observational study of the CVB pressure transmission characteristics in 30 head-injured patients are described.

Clinical Material and Methods

Patient Population

The study population consisted of 30 head-injured patients (20 males and 10 females) with ages ranging from 6 to 62 years old (median age 23 years). On admission, 27 patients scored 8 or less on the Glasgow Coma Scale (GCS), two patients had GCS scores of 9 to 12, and one patient had a GCS score of 13 to 15. Computerized tomography scans showed that 20 patients exhibited focal brain lesions (eight acute subdural hematoma, five chronic subdural hematoma, and seven intracerebral hematoma) and 10 patients presented with diffuse brain injury.

Pressure Monitoring

Patients' ICP and BP were monitored either by Camino catheter-tip transducer systems* or by Medex

* Catheter-tip transducer systems manufactured by Camino Laboratories, San Diego, California.
optimally damped fluid-filled catheter-transducer systems; ICP was monitored subdurally and BP via the radial artery. Fluid-filled catheter-transducer systems, if underdamped, will resonate and can produce significant waveform amplitude and phase distortion.\textsuperscript{8,9} Transient response analysis of the fluid-filled catheter-transducer system currently in use in our head injury intensive care unit has shown that it is underdamped (damping factor 0.310 ± 0.021) with a resonant frequency of 21 Hz. Resonant frequency and damping were determined by the pop test method\textsuperscript{8} and the use of a sinusoidal pressure generator.\textsuperscript{10} Resonant frequency and damping coefficients were calculated by the method of Hanson and Warburg.\textsuperscript{9}

Acudynamic adjustable damping devices\textsuperscript{1} were used to correct underdamping in the fluid-filled catheter-transducer system, and ensure an optimally damped (damping factor 0.622 ± 0.04) flat frequency response with minimal amplitude distortion of the higher harmonics up to 14 Hz. Bench testing determined the optimal setting of the acudynamic adjustable damping devices for standard lengths and diameters of catheters and needles used for pressure monitoring throughout this study. Camino fiberoptic catheter-tip ICP transducers have a resonance well outside our analysis frequency band and, when used with the appropriate high-frequency research monitors, have a flat amplitude frequency response up to 70 Hz.

**Waveform Analysis System Frequency Response**

Waveform data were filtered prior to digitizing by analog fifth order low-pass filters with a corner frequency of 70 Hz rolling off at 30 dB per octave. The entire waveform analysis system, including pressure transducers, preamplifier, patient monitor, frequency modulation (FM) tape recorder, and anti-aliasing low-pass filter, had a flat amplitude frequency response from direct current to 70 Hz ± 1 dB and a linear phase shift of 0.096 radians/Hz. The frequency response of the system was reduced to 14 Hz ± 1 dB when the optimally damped fluid-filled catheter-transducer system was used for pressure measurement. Phase shifts were corrected in software for the linear phase shifts inherent to the waveform analysis system.

**Data Collection**

Five-minute samples of ICP and BP waveform data were stored on magnetic tape by an FM cassette analog data recorder.\textsuperscript{11} Samples were timed to coincide with clinical recordings by the nursing staff and were collected on tape once every 30 minutes during the entire patient monitoring period in the head injury intensive care unit (range 2 to 14 days). Data collection was automated by an IBM-XT microcomputer configured with a general-purpose interface bus adapter\textsuperscript{*} controlling the FM cassette data recorder. With each waveform segment stored on tape, a computer file was created containing the starting tape count and the time and date when the sample was obtained. Comments could be entered and stored to the current computer file at any time, thus permitting precise annotation of significant events.

Waveform data stored on tape was analyzed off-line by a waveform analysis system, developed specifically for this project, based on a 32-bit Apricot Xeni-386 microcomputer.\textsuperscript{17} All software was written in the C programming language. Each waveform segment was digitized at a sampling rate of 400 Hz using a simultaneous sample and hold analog-to-digital converter,\textsuperscript{18} which allows up to four channels to be sampled within 5 nsec. The high sampling rate was selected to avoid errors due to aliasing.

Once digitized, the sampled ICP and BP waveforms were displayed graphically so that a waveform segment free of mechanical and other nonphysiological artifacts could be selected for analysis. A graphics cursor allowed measurement of ICP and BP waveform event amplitudes and periods prior to analysis.

**Data Analysis**

The standard fast Fourier transformation (FFT) algorithm published by Cooley and Tukey\textsuperscript{4} was used to calculate the discrete Fourier transform. A 4096-point FFT was calculated on each waveform segment. The amplitude spectrum was a plot of the modulus of the Fourier transform of a time-dependent signal; the frequency resolution of the amplitude spectrum was 0.098 Hz. The ICP and BP amplitude spectra were displayed and a graphics cursor allowed measurement and recording of the amplitude, frequency, and phase of the spectral peaks at each harmonic component visible in the amplitude spectrum for both the ICP and the BP waveforms.

Systems analysis is a technique whereby an attempt is made to define the physical characteristics of a system using only the system input and output signals (Fig. 1).\textsuperscript{12} It is assumed that the BP waveform is the chief input signal to the cerebrovascular system and the ICP waveform is the output response to that stimulus. The system transfer function is defined as the relationship that describes how the stimulus signals are transformed by the system into response signals.\textsuperscript{13} The transfer function consists of amplitude and phase components.

Both the amplitude and the phase components of the transfer function were calculated from the ampli-

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\textsuperscript{1} Novatrans fluid-filled catheter-transducer systems manufactured by Medex, Inc., Hilliard, Ohio.
\textsuperscript{2} Sinusoidal pressure generator manufactured by Biotek Instruments, Inc., Burlington, Vermont.
\textsuperscript{3} Acudynamic adjustable damping device manufactured by Abbott Critical Care Systems, Chicago, Illinois.
\textsuperscript{4} FM cassette data recorder manufactured by TEAC Corp., Tokyo, Japan.

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\textsuperscript{*} General-purpose interface bus adapter manufactured by IBM UK Ltd., Portsmouth, England.
\textsuperscript{1} Converter manufactured by Data Translation Ltd., Marlboro, Massachusetts.
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Ventilation and Physiological Parameters

All patients whose ICP was monitored had sustained major head injury and were paralyzed and mechanically ventilated with intermittent positive-pressure ventilation. Ventilator and respiratory parameters were recorded and were maintained constant during each segment of ICP recording (ventilation rate 12 breaths/min; percentage inspired time 25%; percentage expired time 65% with a 10% pause; peak inflation pressure 15 to 20 cm H₂O; percentage arterial oxygen saturation > 95%; and end-tidal CO₂ 3 to 4 kPa). With each waveform analysis the following physiological data were recorded: mean ICP, mean systemic BP, mean central venous pressure, and core body temperature. In addition to each ICP and BP waveform collected, the most recently sampled arterial blood gas values (PaCO₂, PaO₂, and pH) were recorded.

Sample Exclusion

Waveform samples were excluded from analysis under the following circumstances: 1) pressure monitoring equipment was blocked, overdamped, or faulty (including catheters, transducers, and fluid-filled connecting tubing); 2) samples were taken from patients with major
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Fig. 2. Graphs depicting four classes of amplitude transfer function for the first six cardiac component harmonics, based on Fourier analysis of 100 pilot samples from a database of intracranial pressure and blood pressure waveforms collected from 30 head-injured patients. The amplitude transfer functions were calculated and found to cluster into four curve types: 1) those with an overall flat amplitude transfer function, 2) those with an elevated low-frequency response, 3) those with an elevated high-frequency response, and 4) those exhibiting both an elevated low- and high-frequency response.

Statistical Analysis

Analysis was carried out using the SPSS statistics package; and, where a specific hypothesis required testing, multivariate analysis of variance and covariance was applied in a random-effects model.

Results

Transfer Function Data

The waveform database comprised 1500 ICP and BP waveform samples (50 per patient); 100 pilot samples from the waveform database underwent spectral analysis. The amplitude transfer functions for the first six cardiac component harmonics were calculated and found to cluster into four curve types (Fig. 2): those with an overall flat amplitude transfer function (curve type 1), those with an elevated low-frequency response (curve type 2), those with an elevated high-frequency response (curve type 3), and those exhibiting both an elevated low- and high-frequency response (curve type 4).

The remaining 1400 samples then underwent spectral analysis and were prospectively coded into the four curve types based on the following criteria. Curve type 1: All harmonics were within 100% of the amplitude of the third harmonic (382 samples). Curve type 2: The first harmonic was at least twice the amplitude of the third harmonic, and all harmonics higher than the first had amplitudes within 100% of the third harmonic (243 samples). Curve type 3: One or more harmonics above the third harmonic was at least twice the amplitude of the third harmonic, and all harmonics higher than the third had amplitudes within 100% of the third harmonic (545 samples). Curve type 4: Any amplitude transfer function not meeting the criteria of...
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FIG. 3. Graphs showing the results of Fourier analysis of the 1400 post-pilot samples from a database of intracranial pressure and blood pressure waveforms collected from 30 head-injured patients, and the amplitude transfer functions prospectively coded into one of four curve types (see legend to Fig. 2 for classification criteria). Data were averaged by amplitude transfer function curve type: curve type 1 = 382 samples, curve type 2 = 243, curve type 3 = 545, and curve type 4 = 202.

curve types 1, 2, or 3 (202 samples). Twenty-eight amplitude transfer functions were excluded because one or more of the higher harmonics were immeasurably small.

The distribution of the amplitude transfer function harmonic samples was found to be log-normal. A log transformation of the data produced an approximately normal distribution with a Kolmogorov-Smirnov (Lilliefors modification) goodness-of-fit test approaching acceptance of the null hypothesis: that is, not significantly different from a normal distribution (0.05 > p > 0.01, with greater than 200 degrees of freedom). The 95% confidence limits were calculated from the transformed data for each of the six harmonics classified by amplitude transfer function curve type. Figures 3 and 4 show the plots for the average amplitude and phase transfer function data, respectively, classified by curve type, together with the 95% confidence limits for each harmonic.

With the phase transfer data, also grouped by amplitude transfer function curve type (Fig. 4), the first harmonic phase shows the least variation of all the harmonics and it is interesting to note that the first harmonic phase for curve type 3 shows a positive phase shift compared to the other curve types, which in terms of the system characteristics is compatible with increased system inductance or its equivalent in mechanical terms (increased inerterness). Also associated particularly with phase transfer function curve type 3, although also present in both curve types associated with elevated ICP (curve types 2 and 4), is the appearance of a phase cross-over from a positive to a negative phase. This phase cross-over was not seen with phase transfer function curve type 1. Phase cross-over is most often associated with systems exhibiting resonance (see Appendix).

Physiological Data

Table 1 presents a breakdown of the physiological data by amplitude transfer function curve type. Blood pressure is not significantly different between groups; however, curve types 2 and 4 (elevated low-frequency and elevated low-frequency response in combination with elevated high-frequency response, respectively) were most often associated with raised ICP (>20 mm Hg) whereas curve types 1 and 3 (flat and elevated high-
FIG. 4. Graphs showing the results of Fourier analysis of the 1400 post-pilot samples from a database of intracranial pressure and blood pressure waveforms collected from 30 head-injured patients and the phase transfer function data, averaged and classified by amplitude transfer function curve type (see legend to Fig. 2 for classification criteria). The first harmonic phase for curve type 3 shows a positive phase shift compared to the other curve types. Also associated particularly with phase transfer function curve type 3 is the presence of a phase cross-over from a positive to a negative phase. This phase cross-over was not seen with phase transfer function curve type 1. Phase transfer function is expressed in radians.

Discussion

This is the first study to demonstrate, through the use of a systems analysis approach, clearly definable patterns of pressure transmission across the CVB in a head-injured population. A consideration of the observed data based on amplitude transfer function curve type in relation to previous work by us and others, although speculative, may prove useful as an aid to interpreting these results.

Amplitude Transfer Function

**Curve Type 1 (Flat).** A flat amplitude transfer function was associated mostly with ICP below 20 mm Hg (mean 15 mm Hg). This represents linear transmission of the arterial pressure waveform through to the cerebrospinal fluid (CSF) space. Kasuga, et al., noted a decreased pressure transmission in the low-frequency range of 1 to 7 Hz in their control group of dogs with normal ICP (7 to 10 mm Hg) which tended to increase with ICP at or near 15 mm Hg. Similarly, Portnoy, et al., observed attenuation of the fundamental harmonic component in the transmission of the arterial pulse through to the CSF space under conditions of low ICP (< 7 mm Hg), attributing this nonlinear transmission to functional autoregulatory tone of the pre-capillary cerebral resistance vessels, and further demonstrating that linear transmission can be experimentally induced by intraventricular infusion of mock CSF or arterial hypercarbia. They propose that the conversion from nonlinear to linear transmission is evidence for loss of arteriolar vasomotor tone. In hydrocephalic dogs, Portnoy, et al., found nonlinear transmission
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**TABLE 1**

*Physiological data collected with each waveform sample by amplitude transfer function curve type*

<table>
<thead>
<tr>
<th>Curve Type</th>
<th>No. of Samples</th>
<th>Mean ICP (mm Hg)</th>
<th>Mean BP (mm Hg)</th>
<th>Mean CVP (mm Hg)</th>
<th>Core Body Temperature (°C)</th>
<th>PaCO₂ (kPa)</th>
<th>PaO₂ (kPa)</th>
<th>pH (nmol/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>382</td>
<td>15 ± 9</td>
<td>90 ± 15</td>
<td>1.2 ± 2.8</td>
<td>37.2 ± 1.0</td>
<td>3.6 ± 0.7</td>
<td>18.8 ± 3.8</td>
<td>33.6 ± 3.7</td>
</tr>
<tr>
<td>2</td>
<td>243</td>
<td>24 ± 10</td>
<td>86 ± 10</td>
<td>2.7 ± 3.8</td>
<td>37.3 ± 0.6</td>
<td>3.3 ± 0.6</td>
<td>19.2 ± 3.9</td>
<td>31.5 ± 3.3</td>
</tr>
<tr>
<td>3</td>
<td>545</td>
<td>13 ± 10</td>
<td>85 ± 15</td>
<td>1.9 ± 2.9</td>
<td>37.4 ± 0.7</td>
<td>3.5 ± 0.6</td>
<td>18.1 ± 3.5</td>
<td>34.2 ± 4.5</td>
</tr>
<tr>
<td>4</td>
<td>202</td>
<td>30 ± 19</td>
<td>86 ± 10</td>
<td>1.6 ± 3.1</td>
<td>36.7 ± 1.3</td>
<td>3.6 ± 0.3</td>
<td>18.4 ± 3.2</td>
<td>34.0 ± 1.5</td>
</tr>
</tbody>
</table>

* Values are means ± standard deviations. ICP = intracranial pressure; BP = blood pressure; CVP = central venous pressure.

when ICP was below 9 mm Hg and linear transmission when ICP was greater than 12 mm Hg.

The mean ICP in our curve type 1 group (15 mm Hg) is within the ICP range associated with linear pressure transmission as reported by Portnoy, et al., and the increased low-frequency pressure transmission as reported by Kasuga, et al. This observed linear transmission cannot be attributed to arterial hypercarbia as all patients were maintained normocarbic (Table 1). These reports support the view that the amplitude transfer function curve type 1, despite its association with lower ICP, may indicate reduced cerebrovascular tone.

Curve Type 2 (Elevated Low Frequency). Amplitude transfer function curve type 2 was characterized by an elevated low-frequency pressure transmission which was most often associated with ICP above 20 mm Hg. It was chiefly the fundamental harmonic component that was elevated. Portnoy and Chopp, Takizawa, et al., demonstrated the dependence of the fundamental harmonic component in the amplitude transfer function on CO₂-induced alterations in cerebrovascular resistance. In support of these studies we have shown in head-injured patients that, during progressive hypocapnia induced through the removal of excess ventilatory dead space, it is predominantly the fundamental harmonic component that is affected by CO₂-induced alterations in vascular resistance, higher harmonics showing little or no effect.

Portnoy, et al., suggested that a greatly increased transfer of the fundamental harmonic component may be a marker for failure of myogenic autoregulation. An increased fundamental harmonic transmission could be due either to loss of autoregulatory tone or paradoxically to intact autoregulation compensating for reduced cerebral perfusion pressure through active vasodilation. Some measurement of local CBF or flow/metabolism coupling, such as the arterial-to-jugular bulb oxygen difference, would be required to distinguish these conflicting mechanisms.

These studies support the hypothesis that elevated low-frequency cerebrovascular pressure transmission may be an indication of vascular mechanisms underlying raised ICP.

Curve Type 3 (Elevated High Frequency). In this study, a high proportion (40%) of amplitude transfer functions demonstrated elevated high-frequency harmonics without an associated increased fundamental harmonic component. This was mostly associated with an ICP below 20 mm Hg.

Kasuga, et al., applying pressure pulse waves into the CVB, demonstrated a resonance in the intracranial compartment in dogs (see Appendix for a discussion of cerebrovascular resonance). This resonant peak occurred under control conditions in the higher-frequency range from 10 to 15 Hz, a frequency which is nearly within range of the fifth and sixth harmonics of the amplitude transfer function. They demonstrated that the resonant frequency increased when ICP was experimentally increased by intraventricular infusion of mock CSF or through inflation of an extradural balloon.

Bray, et al., and Robertson, et al., in clinical studies of the power-density spectrum of the ICP waveform, showed two predominant frequency bands; they associated the higher band (4 to 15 Hz) with the ringing or resonance properties of the intracranial compartment and they demonstrated a strong inverse correlation between the frequency at which the resonant peak of the high-frequency band occurred and intracranial compliance as measured by the pressure-volume index. That is, as intracranial compliance decreased, the resonant frequency increased. They further demonstrated that an increase in the frequency of resonance above 9.0 Hz was predictive of poor outcome in patients.

These reports would support the hypothesis that an elevated high-frequency pressure transmission, as seen with the amplitude transfer function curve type 3, is an indication of the start of a resonant peak in the transfer function, and its detection is indicative of high intracranial compliance and a favorable prognosis of ICP. A state of reduced compliance, either with or without raised ICP, will tend to increase the resonant frequency beyond that of the frequency of the sixth harmonic and hence the level of detection by this method. This would result in the transformation from a curve type 3 amplitude transfer function to another form (curve types 1, 2, and 4) which may be predictive of, or associated with, raised ICP.
Waveforms were collected from a stable normotensive, study population, 30 sequential samples of ICP and BP that it is principally the fundamental harmonic component of the amplitude transfer function which is of interest, particularly with regard to changes in precapillary cerebrovascular resistance, stating further that harmonics higher than the fourth harmonic exhibit too much variance.

A measure often used in describing the amount of variation in a population is the coefficient of variation (CV): $CV = (\text{sample standard deviation/sample mean}) \times 100$. To assess the variance of our method in the study population, 30 sequential samples of ICP and BP waveforms were collected from a stable normotensive, normovolemic head-injured patient with normal ICP. The mean and standard deviation for each of the first eight cardiac component harmonics were calculated and expressed as the CV. Figure 5 is a plot of the CV for each of the first eight cardiac component harmonics from the amplitude and phase transfer functions recorded in a head-injured patient in stable condition. The first five harmonics of the amplitude transfer function data (closed circles) show a coefficient of variation less than 10%, the sixth and seventh show a variation of between 20% and 30%, and the eighth harmonic shows a variation of greater than 45%. With the phase transfer function data (open circles), only the first harmonic shows a coefficient of variation of less than 20%.

Study Methods

Portnoy and coworkers and Takizawa, et al., using similar methods in experimental models of raised ICP, reported frequency-dependent changes in the amplitude transfer function. Portnoy, et al., maintained that it is principally the fundamental harmonic component of the amplitude transfer function which is of interest, particularly with regard to changes in precapillary cerebrovascular resistance, stating further that harmonics higher than the fourth harmonic exhibit too much variance.

A measure often used in describing the amount of variation in a population is the coefficient of variation (CV): $CV = (\text{sample standard deviation/sample mean}) \times 100$. To assess the variance of our method in the study population, 30 sequential samples of ICP and BP waveforms were collected from a stable normotensive, normovolemic head-injured patient with normal ICP. The mean and standard deviation for each of the first eight cardiac component harmonics were calculated and expressed as the CV. Figure 5 is a plot of the CV for each of the first eight cardiac component harmonics from the amplitude and phase transfer functions recorded in a head-injured patient in stable condition. For the amplitude transfer function data, the first five harmonics have a CV of less than 10%, the sixth and seventh show a CV of between 20% and 30%, and the eighth harmonic shows a CV of greater than 45%. With the phase transfer function data, only the first harmonic shows a CV of less than 20%, harmonics higher than the fourth showing very large variation between repeated measurements. Our data analysis was therefore confined to the first six cardiac component harmonics of the amplitude transfer function and the first cardiac component harmonic of the phase transfer function.

Similar to Portnoy, et al., we noted that the higher harmonics exhibit a greater variance. However, the significance of the higher harmonics should not be underestimated, particularly in view of this study's findings of a high rate of occurrence (54%) of amplitude transfer functions with elevated higher-frequency harmonics either with or without an associated increased fundamental harmonic component (curve types 3 and 4).

Kasuga, et al., have been critical of the spectral analysis method for determination of the transfer function. The method is limited by the frequency information present in the input and output pressure waveforms and is thereby forced to assume a linear transfer between measured pressure harmonics. As a result, the spectral analysis method has limitations for accurate measurement of the resonant frequency. The use of a controlled randomized input function for determination of the transfer function is superior to the spectral analysis method but as yet is not clinically practical.

The radial artery and the subdural space are not ideal measurement sites for BP and ICP, respectively. Measurement of BP in the carotid artery, although closer to the input of the CVB, is clinically and ethically not practical. If a transfer function analysis of the CVB is shown to provide information of clinical importance to the management of head-injured patients, then its methods must be clinically practical. Our pilot investigations indicated that there are differences between transfer functions calculated at the radial, femoral, and carotid BP measurement sites. The errors caused, however, appear to be no greater than the inherent variability of the method from repeated measurements: that is, between 20% and 30% for the amplitude transfer function data. The phase transfer function is greatly affected by the BP measurement site and its high variability precludes its routine use for harmonics.
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**Fig. 6.** Left: Schematic drawing modeling the cerebrovascular bed as a single elastic tube in which the terminal portions of the tube have an impedance large enough to be considered completely closed, resulting in no flow from the end and a pressure pulse that is fully reflected back toward the input of the tube. In view of the pressure, with respect to time, at three distances (A, B, and C) along the length of the tube, reflection can lead to the formation of a standing wave pattern where, at repeated fixed distances along the tube (distance C), incident and reflected pressure waves coincide resulting in addition, which is measured as an amplification of the pressure pulse at that point. Right: A standing wave pattern is set up where, at each distance along the length of the tube where incident and reflected pulse waves coincide, a peak occurs in the amplitude transfer function and the phase transfer function demonstrates a phase cross-over. The frequency with which the incident and reflected pressure waves coincide is termed the "resonant frequency" and is determined by the physical characteristics of the tube. (Figure adapted from Taylor MG: An introduction to some recent developments in arterial haemodynamics. *Aust Ann Med* 15:71-86, 1966.)

above the first cardiac component harmonic. These errors become limiting factors only if one attempts to draw conclusions from subtle changes in the transfer function, particularly with the higher harmonics. Large changes, as reported here in the form of the four amplitude transfer function curve types, are easily distinguishable.

Placement of an intraventricular pressure monitor, particularly in patients with collapsed ventricles or midline shift, is often not possible. In these cases, the use of the subdural space for ICP recording is feasible provided that a catheter-tip transducer system is used for monitoring pressure. A catheter-tip transducer system, such as the Camino system, is less likely to become overdamped through compression of the CSF space than a fluid-filled catheter-transducer system.15

**Conclusions**

This observational study demonstrated the presence and defined the inherent variability of specific patterns of pressure transmission across the CVB in head-injured patients. This work provides the foundation for future clinical studies designed to follow minute-by-minute changes in cerebrovascular pressure transmission in head-injured patients with respect to the development of raised ICP and its effectiveness as a predictor of the choice of therapy. Studies of this type may provide insight into the pathophysiology of the CVB and ultimately aid the prediction and treatment of raised ICP.

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**APPENDIX**

The phenomenon of resonance in the CVB is best understood in relation to vascular impedance. Pressure transmission across the CVB is determined by cerebrovascular impedance. In a fluid system, resistance is defined in terms of the pressure gradient and fluid flow in the steady state, that is, under conditions independent of the time of measurement. Impedance, however, is a term used to define pulsatile or oscillating pressure and flow, a time-dependent relationship. Provided that CSF pressure exceeds sagittal sinus pressure, ICP approximates cerebral venous pressure.13,29 Although clinically we are unable to measure cerebrovascular impedance directly, simultaneous measurement of systemic arterial pressure and ICP waveforms (ICP waveform as a measure of the cerebral venous pressure waveform) provides measures of input and output functions to the CVB, which allow one to infer changes in the impedance of the CVB. Considering the theoretical case where the CVB is modeled as a single elastic tube (Fig. 6), if the terminal portions of the CVB have an impedance that does not match the impedance of the input segment of the CVB, pressure wave reflection phenomena can occur. Wave reflection is a fundamental property of resonance. The type of reflection will depend on the nature of the terminating impedance. Reflection can lead to the formation of a standing...
pressure wave pattern where, at repeated fixed distances along the CVB, incident and reflected pressure waves coincide resulting in addition, which is measured as an amplification of the pressure pulse at that point. The frequency with which the incident and reflected pressure waves coincide is termed the “resonant frequency”.25

In reality, the CVB is not a single elastic tube but a network of arterial and venous blood vessels, each with a characteristic impedance. O’Rourke and Taylor,14,28 studying the impedance of the femoral bed in dogs, did not find this standing wave pattern and argued that, as the arterial system has many terminations at varying distances from the heart, the reflected oscillations returning from these scattered terminations will tend to cancel. The increase in arterial stiffness toward the terminations at varying distances from the heart, the reflected pressure wave pattern where, at repeated fixed distances along the CVB, incident and reflected pressure waves coincide is termed the “resonant frequency”.25

Unlike the femoral vascular bed, however, the CVB is unique in its rigid self-contained enclosure with high outflow resistance, where the distances covered by the cerebrovascular system are small compared with the cardiovascular system. Furthermore, raised ICP will cause compression of the more compliant and collapsible cerebral venous vessels such as the cerebral bridging veins and lateral lacunae.15 This may result in a near-perfect closed terminating impedance to the CVB, an ideal source of reflection phenomena.

References

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