Estimating Brain Compliance Based on a Novel Model of Intracranial Cerebrospinal Fluid Dynamics

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Abstract- **The assumption that cerebrospinal fluid (CSF) inflow and outflow is an essential element of an intracranial compartment (IC) model has been recently questioned [3]. The idea proposed in [3] that the free displacement of the CSF is one of the significant sources of the brain compliance is supported in this paper by computing an overall system compliance with a novel algorithm. The compliance obtained using the proposed method is shown to be in the same order of the magnitude as that obtained using the traditional intrusive infusion test technique.**

Keywords **- Intracranial pressure, lumped model, venous flow**

I. Introduction

Intracranial pressure (ICP) has been traditionally considered a function of the CSF production rate (I_f) and the outflow resistance (R_{out}) [1]. Lumped circuit models of the IC have thus considered the CSF compartment as a current source and resistance [2]. This concept has been challenged as a result of dynamic MRI studies that suggest an alternative role of CSF [3]. These studies suggest that the dynamic movement of CSF is the primary IC compliance mechanism responding to the hemodynamic consequences of pulsatile arterial flow [4]. Based on this representation, the CSF compartment should be modeled as a capacitor that somewhat corresponds to IC compliance.

II. Methodology

In this study, a novel IC circuit model was investigated by analyzing the data derived from a surrogate *in vivo* IC model. As an approximation of the IC, the kidney of a rabbit was enclosed within a fluid-filled, rigid-box surgically positioned within the pelvis. The box fluid pressure (~ICP), renal arterial and renal venous blood flow signals were collected in an open-box and a closed-box case (corresponding to high and low compliance IC states). Using the continuous arteriovenous difference in blood volume and box pressure, a dynamic pressure-volume (p-v) curve was estimated. The compliance of the system was then computed as the slope of this p-v curve. This value was found to be comparable to the value determined by the direct in vivo estimation of the compliance. As expected, the dynamic compliance calculated for an open-box is significantly higher than that of a closed-box case.

A. The animal experiment

The simulated IC was based on a New Zealand white rabbit kidney enclosed in a rigid saline-filled box with an port on top (corresponding to the foramen magnum). Occlusion of the port was considered the "closed-box case". Using the standard infusion test, the kidney capsule compliance (and hence box compliance) was estimated from a p-v curve generated by a controlled arterial volume infusion. The details of the experiment can be found in [5].

B. The model

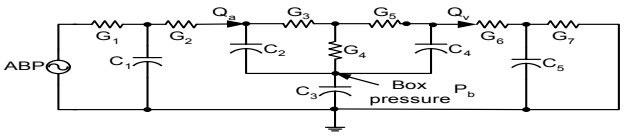

Fig.1. An equivalent circuit model of a kidney within a rigid box

We modified a standard ICP model [2] by removing the CSF outflow resistor and incorporating the compliance due to CSF free displacement into the compliance element (C_3, Fig.1) which only represented brain tissue compliance in the original model.

We suggest that this model is suitable for the simulated IC. In this context, the proximal arterial portion from the place where arterial blood pressure (ABP) was measured down to the entrance of the renal artery to the kidney was represented using a three-element (G_1, G2 and C_1) Windkessel model and so was the distal venous portion (G_6, G_7 and C_5). The kidney enclosed within a rigid box was represented as the middle portion of the circuit.

Even without incorporating any nonlinear effects, the identification of this linear dynamic model requires more state measurements than we have collected. If C_3 is considered time-invariant, the following relationship holds:

$$\frac{d}{dt}P_b(t) = \frac{Q_A(t) - Q_v(t)}{C_3} \quad (1)$$

It means that C_3 can be characterized using P_b, Q_a and Q_v. The $dP_b(t)$ is approximated as:

$$dP_b(t) = [2P_b(t+t_s) - 1.5P_b(t) - 0.5P_b(t+2t_s)]/t_s \quad (2)$$

where t_s is the sampling time. C_3 can be visualized by plotting dP_b as the x-axis with $Q_a - Q_v$ being the y-axis. This curve is called the compliance curve hereafter.

C. Pressure-volume curve

Two representative compliance curves from two consecutive cardiac cycles are shown in panels B and C of the Fig.2. As revealed in the hysteresis-like shape of the curve, C_3 appears to be a nonlinear element. However, to estimate the global compliance of the system, we propose here an algorithm to derive a p-v curve from the compliance curve and then use it to compute an equivalent global compliance value of the system. Of note, a p-v curve is a standard way of determining the compliance of the IC. However, it is usually generated by injecting certain amount of fluid in a constant rate into the system. Only the first or

the third quadrant part of a compliance curve should be used because an either increasing or decreasing curve is expected to produce a physically meaningful curve. In the first case, due to the lag between the arterial input and the venous output, the volume of the system is increasing and the pressure is also increasing, which is similar to an infusion test. The second case corresponds to a withdrawal test. Only the first "infusion" case was considered in this paper.

The p-v curves shown in panels E and F of Fig.2 were generated from the first quadrant part of the compliance curves shown in panels B and C respectively (the points falling in the first quadrant were marked with stars). The flow difference between the renal artery and the renal vein was numerically integrated to obtain an estimation of the volume "infused" into the system.

After obtaining a pressure-volume curve, the compliance is calculated as the slope of a straight line fitted to it and there is one p-v curve per cardiac cycle.

D. Data and preprocessing

Data from four separate rabbit experiments were analyzed. In each experiment, a transition from open to closed box was repeated several times. The measured signals included box pressure (P_b, dyne/ cm^2) and arterial and venous flow (Q_a and Q_v, ml/s). All the data were sampled at 200Hz. To suppress the measurement noise, a 20^{th}-order low-pass finite impulse response (FIR) filter with a cutoff frequency at 10Hz was applied to the measured signals.

III. RESULTS

All the p-v curves generated from the data during the closed-box phase of one experiment are shown in the upper panel of Fig.3 along with the mean and standard deviation of the compliance computed from them. For the same rabbit, a standard infusion test was also conducted in the closed-box phase. The resulting p-v curve is shown in the lower panel. The compliance value computed from fitting the portion of this curve between two open circles was 3.45e-6 cm^5/dyne, which is in the same order of magnitude as the compliance computed using the proposed algorithm (1.94e-6 cm^5/dyne).

The mean compliances of the two phases pooled for all the data obtained in each experiment are listed in the Table 1 together with the p-value from a t-test of the null hypothesis that compliance in the open-box case is significantly larger than that of the closed-box case ($p < 0.01$).

IV. DISCUSSION

The results obtained here support our conjecture that container compliance can be estimated using the arteriovenous volume difference and the measured container pressure. Future studies will be required to determine prospectively whether this modeling and analysis approach is valid for the IC. Clinically, our proposed method may allow the estimation of the overall intracranial compliance using carotid artery and jugular vein flow probes in conjunction with an indwelling ICP monitor (without the need for an infusion bolus study).

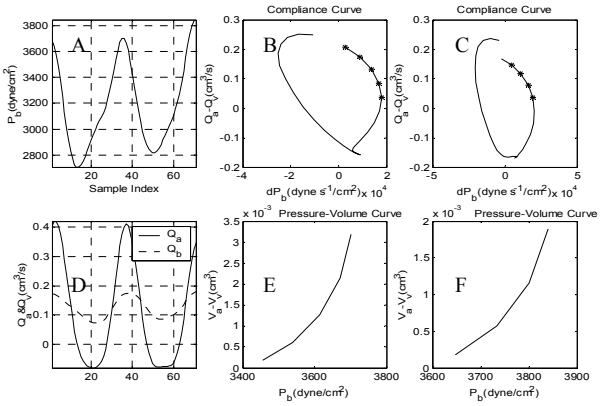

Fig.2. P_b is shown in the panel A with Q_a and Q_v in the panel D. In B and C, compliance curves are shown with corresponding p-v curves in E and F.

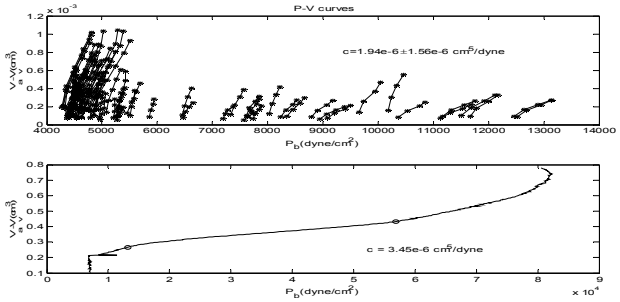

Fig.3. The p-v curves generated using our algorithm for the close-box case in one experiment are shown in the upper panel. For the same rabbit in the closed-box phase, a p-v curve from using standard infusion test is shown in the lower panel.

TABLE 1
Comparison of the compliances in the open and closed box.

Exp. No	Mean ± Std (cm^5/dyne)		p-value
	Open box	Closed-box	
1	1.15±0.79E-04	1.02±0.30E-05	0.0
2	1.62±0.69E-05	7.70±9.37E-08	0.0
3	9.96±4.99E-06	3.76±1.30E-07	0.0
4	8.66±7.12E-06	2.95±2.79E-07	0.0

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