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Lessons learned measuring peripheral venous pressure waveforms in an anesthetized pediatric population

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Abstract

Objectives: The purpose is to describe our institution's experience with collecting peripheral venous pressure (PVP) waveforms using a standard peripheral intravenous catheter in a pediatric patient under general anesthesia. *Approach:* PVP waveforms, piezoelectric monitoring, arterial blood pressure recording, and electrocardiogram (EKG) tracings were collected from patients undergoing cranial vault reconstruction for craniosynostosis. Data was obtained prospectively in a continuous manner from time of patient final positioning to closure of incision. Description of the technical aspects are discussed. *Main Results*: The waveform data collection was affected by the following: use of electrocautery, location of electrocautery in relation to PVP monitor, and movement of the operating room table. *Significance:* PVP waveforms can be collected in a pediatric patient undergoing general anesthesia with accurate data acquisition. Additionally, the set-up used also allows for accurate collecting of piezoelectric monitoring, arterial blood pressure recording, and EKG tracings in real time.

Introduction

Craniosynostosis is a disorder caused by the premature closure of one or more cranial sutures in the infant skull. The gold standard operation to correct this condition is cranial vault remodeling (CVR) which involves extensive craniectomies and reconstruction to increase intra-cranial volume and concomitantly normalize calvarial shape. Due to the vast blood supply to the skull, intra-operative estimated blood loss can range from 20–60 ml kg^{-1} [1, 2]. Presently, intra-operative resuscitation is guided by invasive arterial blood pressure recording and serial hemoglobin evaluation. Ideally, non-invasive real-time monitoring would be available.

Hocking demonstrated in both an adult porcine model and adult hemodialysis patients that Fast Fourier Transform (FFT) of a peripheral venous pressure (PVP) waveform correlated with volume status [3, 4]. Subsequently, our group has applied similar technology in a young piglet model, analyzing PVP waveforms in addition to arterial blood pressure recordings, electrocardiogram (EKG) tracing data, and piezoelectric monitoring. Additionally, we then published our experience with PVP waveform acquisition and analysis performed in an awake pediatric patient [5]. We have recently accrued PVP waveforms during CVR cases, which provides a clinical model to study acute hemorrhage.

The aims of this manuscript are to: (1) describe the technical aspects of PVP waveform, piezoelectric monitoring, arterial blood pressure recording, and EKG tracing data collection in anesthetized pediatric patients and (2) discuss the lessons learned to optimize the acquisition of accurate data.

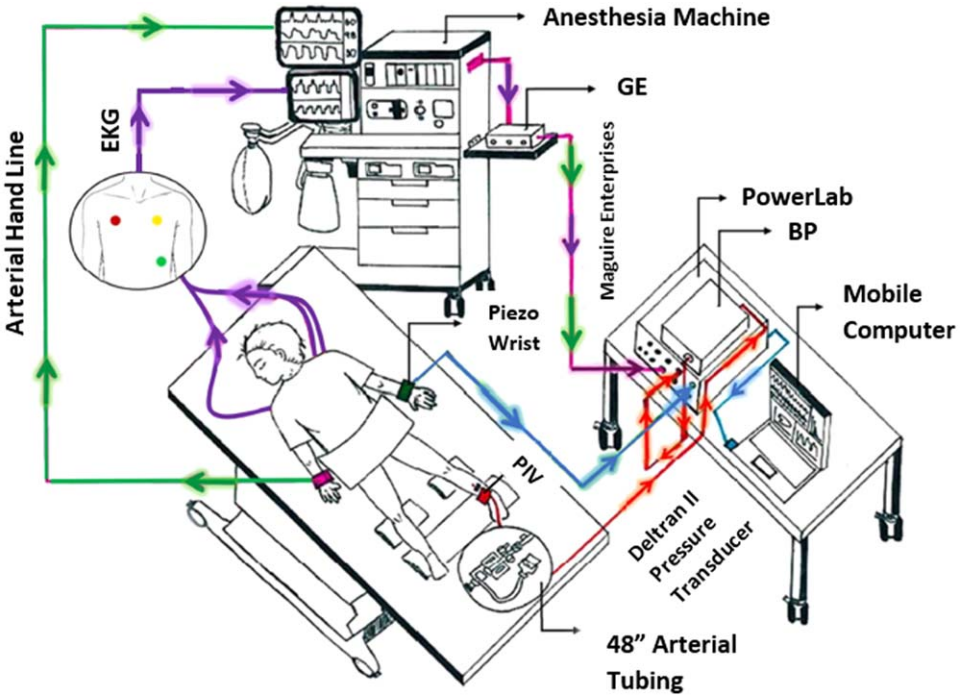

Figure 1. Data acquisition setup including Insyte IV 48 inch arterial tubing, Deltran II pressure transducer (red), BP Amp, Powerlab, and Labchart. Additional data points include Arterial waveform (green), EKG (purple), and piezoelectric monitor (blue).

Methods

After IRB approval, data was collected from patients undergoing CVR for craniosynostosis. PVP waveforms, piezoelectric monitoring, arterial blood pressure recording, and EKG tracings were collected continuously from final patient positioning in the operating room until closure of incision.

PVP waveform data was collected in a closed system via a 22-gauge Insyte-N Autoguard PIV catheter (Becton Dickinson Infusion Therapy Systems, Sandy, Utah, USA) connected to a 48 inch arterial pressuring tubing (Smiths Medical, Dublin, OH, USA). The arterial pressure tubing was connected to a Deltran II pressure transducer (ADInstruments, Colorado Springs, CO, USA) interfaced with a Powerlab data acquisition system. Pulse monitoring was performed with a Piezoelectric TN1012/ST Pulse Transducer element placed on the skin over a peripheral artery (radial or dorsalis pedis). The transducer was interfaced with a PowerLab data acquisition system (ADInstruments).

Using an optimizer cable with output multiplier capabilities (Maguire Enterprises, Fort Lauderdale, FL, USA), EKG tracings and arterial blood pressure recordings were collected via direct interface with a Powerlab data acquisition system at a sample rate of 1000 samples per second (1 kHz) (figure 1).

Data was collected prospectively. The PVP waveform was zeroed at the time of final patient positioning prior to incision. The quality of the arterial blood pressure recording and EKG tracing are accurate as they are directly transmitted from the operating room software. The piezoelectric recording quality was confirmed as correlation to the EKG tracing with voltage noted for each heartbeat. The quality of the PVP waveforms were evaluated by noting changes to waveforms by external influences in the operating room and correlating changes to the waveform with both piezoelectric recordings and EKG tracings. Using LabChart (ADInstruments, Colorado Springs, CO, USA), figures were obtained at a 10:1 horizontal scaling. The *y*-axis (pressure in mmHg) and *x*-axis (time in seconds) were adjusted for demonstrative purposes. The analysis routines deployed when extracting critical information from this data are able to work on signals that have a large variety of quality parameters. Hence, the assessment for determining if the signal quality was appropriate for further analysis was qualitative, but not part of a formal procedure.

Preprocessing of data

The collected data are preprocessed with statistical methods to remove anomalies caused by undesired artifacts such as patient movements. Based on our observation, artifacts such as unintended patient movement will create significant fluctuations in the waveform over a short period of time. Thus, anomalies in the data can be identified by detecting the presence of such fluctuations. On the other hand, hemodynamically significant hemorrhage might also cause large signal fluctuations. Thus, it is important to distinguish between fluctuations caused by patient movement from hemorrhage and only remove those contaminated by patient movement.

For each patient, the time series PIV data is fragmented into non-overlapping frames of duration 10 s each. Denote the jth frame of the ith patient as $x_{i,j} = [x_{i,j}[1], x_{i,j}[2], \ldots, x_{i,j}[m]]$, where m is the total number of samples in a frame. With a sampling rate of 1 KHz and a frame duration of 10 s, there are m = 10 K samples in each frame. The sample mean, $\bar{x}_{i,j}$, and the sample variance, ${s_{i,j}}^2$, of each frame can be calculated by

$$\bar{x}_{i,j} = \frac{1}{m}\sum_{k=1}^{m} x_{i,j}[k]$$

$${s_{i,j}}^2 = \frac{1}{m-1}\sum_{k=1}^{m}(x_{i,j}[k] - \bar{x}_{i,j})^2$$

The sample variance ${s^2}_{i,j}$, can be used as a measure of the degree of fluctuation in one frame. Based on the observation that more fluctuations are present at frames with motion artifacts, we can detect the presence of such artifacts by comparing ${s^2}_{i,j}$ among frames from the same patient. Since motion artifacts will cause large fluctuation in a frame, the sample variance, $\{{s^2}_{i,j}\}_j$, belonging to different frames of the same patient are in general not identically distributed. We thus propose to detect frames with anomalies in a two-step procedure. In the first step, frames with excessively large sample variances are first removed to avoid bias in the subsequent statistical analysis. In the second step, additional frames are removed based on statistical analysis of all remaining frames, the sample variances of which are assumed to be identically distributed in the analysis.

In the first step, frames with excessively large sample variances are removed. Specifically, the jth frame from the ith patient is removed if

$${s^2}_{i,j} > a$$

where a is a predefined parameter. Based on the observations of all collected PIV signals, the threshold is chosen to be a value less than 10. After the removal of the frames with excessively large sample variance, assume there are f_i^* frames remaining out of original f_i frames of ith patient.

In the second step, statistical analysis is performed over the remaining frames to further remove any additional anomalies. It is important to distinguish between fluctuations caused by patient movement from those caused by hemodynamically significant hemorrhage, such that only frames affected by patient movement are labeled as anomalies and removed. Fluctuation can be measured by the variance of the signal. It is observed that if the fluctuation is caused by patient movement, then the value of the variance changes dramatically within a frame. On the other hand, for signal fluctuations caused by hemorrhage, the variance increases but then remains at a large value for a relatively longer period of time. Thus we can detect patient movement by measuring the variation of the signal variance within one frame. That is, if the signal variance changes dramatically within a frame, then the frame is deemed as an anomaly and removed.

To measure to variation of variance within a frame, the variance is calculated and updated by using a sliding window of size w_s, where $w_s < m$ with m being the size of a frame. For the jth frame from the ith patient, the signals within the kth sliding window can be represented as $[x_{i,j}[k], x_{i,j}[k+1], \ldots, x_{i,j}[k+w_s-1]]$, where $k = 1, 2, \ldots, m - w_s + 1$. The mean and variance of signals in the kth sliding window can thus be calculated by

$$\bar{x}_{i,j,k} = \frac{1}{w_s}\sum_{p=k}^{k+w_s-1} x_{i,j}[p]$$

$${s_{i,j,k}}^2 = \frac{1}{w_s-1}\sum_{p=k}^{k+w_s-1}(x_{i,j}[p] - \bar{x}_{i,j,k})^2$$

where ${s_{i,j,k}}^2$ is the variance of kth sliding window within the jth frame of the ith patient, and there are $m - w_s + 1$ variances within each frame.

Based on observations of the collected data, patient movement will cause a large variation among the $m - w_s + 1$ variances inside each frame. The variation of the variances inside each frame can be measured by using the sample variance of the $m - w_s + 1$ variances, which can be calculated by,

$$\overline{{s^2}_{i,j}} = \frac{1}{m+1-w_s}\sum_{k=1}^{m+1-w_s} {s_{i,j,k}}^2$$

$$\langle {s^2}_{i,j}\rangle = \frac{1}{m-w_s}\sum_{k=1}^{m+1-w_s}({s_{i,j,k}}^2 - \overline{{s^2}_{i,j}})^2$$

For a frame that contains valid data, the sample variance of sliding window signal variances within each frame should be very small, even though the sliding widow itself could be large due to patient hemorrhage. On the other hand, for frames that contain bad data due to patient movement, the value of $\langle {s^2}_{i,j}\rangle$ could be large due to the time variations of the signal variances. Thus we propose to remove frames with $\langle {s^2}_{i,j}\rangle$ above a certain threshold.

The removal threshold is calculated by using the average and standard deviation of $\langle {s^2}_{i,j}\rangle$ from all frames of the same patient. Define

$$\mu_i = \frac{1}{f_i^*}\sum_{j=1}^{f_i^*}\langle {s^2}_{i,j}\rangle$$

$${\sigma_i}^2 = \frac{1}{f_i^*-1}\sum_{j=1}^{f_i^*}(\langle {s^2}_{i,j}\rangle - \mu_i)^2$$

which are the mean and variance of $\langle {s^2}_{i,j}\rangle$ from the ith patient. Then the jth frame is discarded if

$$\langle {s^2}_{i,j}\rangle > \mu_i + b\sigma_i$$

where b is a small number used to adjust the percentage of rejected frames.

In case of removing artifacts from the data collected from 6 patients in this study, setting $w_s = 100$, a = 5 and $b = -0.1$ has successfully accepted 80.4%

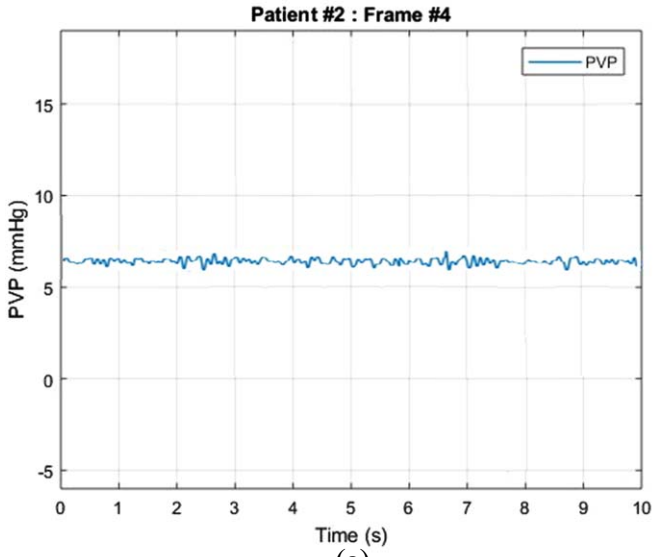

Figure 2. Waveform examples of a good frame (#4) and a motion artifact corrupted frame (#5). (a) 'Good' frame with periodic nature. (b) 'Bad' frame, notice the abrupt change in signal amplitude.

of the recorded frames. Apart from only PVP signal, other auxiliary signals collected during the collection of PVP like EKG and arterial pressure can also help to eliminate corrupted frames. Simultaneous occurrence of interference in PVP and auxiliary signal can indicate that there is a disturbance that is causing anomalies in both signals.

As an example, figures 2(A) and (b) show a good frame (#4) and a motion artifact corrupted frame (#5), respectively, from patient #2 (figures 2(A), (B)). For these two frames $\langle s^2_{2,4} \rangle = 0.001$ and $\langle s^2_{2,5} \rangle = 40.9$, respectively. The threshold here is $\mu_i + b\sigma_i = 2.06$. Figure 3 plots $\langle s^2_{2,j} \rangle$ for all the frames of patient #2. Frames with $\langle s^2_{2,j} \rangle$ greater than the threshold $\mu_i + b\sigma_i = 2.06$ are discarded (figure 3).

Results

Data were collected from six patients. The mean age was 10.2 months (range: 3–37 months) and 83% were males. A baseline image from LabChart including PVP waveform, piezoelectric tracing, arterial blood pressure recordings, and EKG tracings is shown in the figure (figure 4). The type of craniosynostosis repair included: Cranial vault reconstruction with fronto-orbital advancement (n = 4), posterior vault reconstruction (n = 1), and endoscopic sagittal cranioplasty (n = 1).

Interference in data collection was associated with use of electrocautery, location of electrocautery in relation to PVP monitor, and movement of the operating room table. Movement artifacts were clearly visible in the acquired datasets.

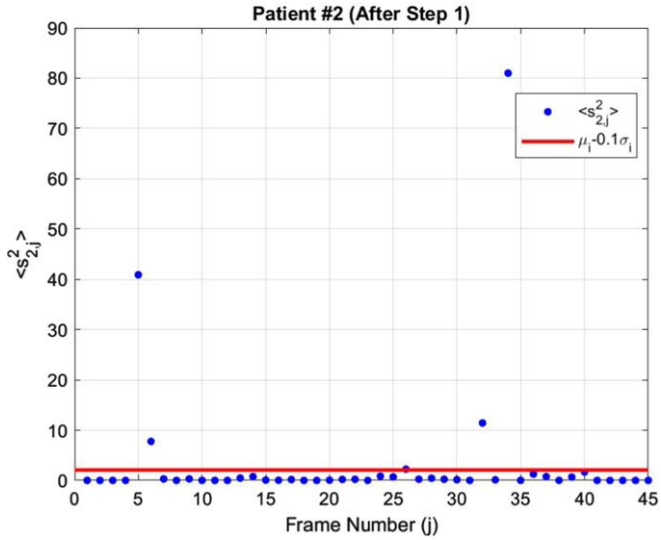

Figure 3. Plot of $\langle s^2_{2,j} \rangle$ from all the frames of patient #2. Frames having $\langle s^2_{2,j} \rangle$ greater than the threshold are discarded. The threshold here is $\mu_i - 0.1\ \sigma_i = 2.06$ (figure 3).

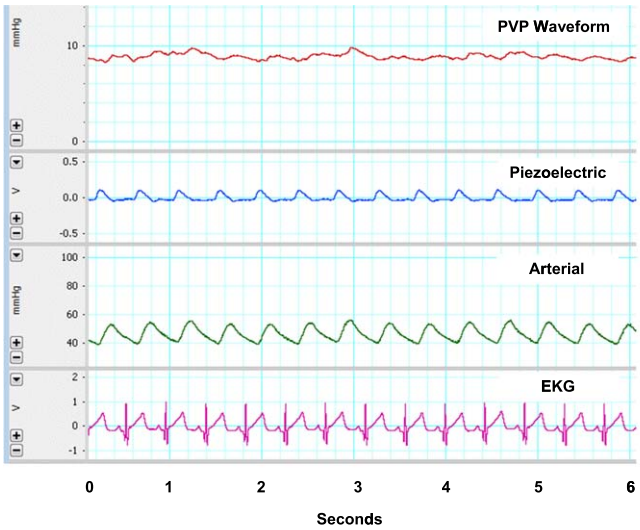

Figure 4. Normal waveform from Labchart of the peripheral venous pressure, piezoelectric monitoring, arterial blood pressure, and EKG measured in seconds.

Electrocautery (bipolar)

General

The PVP waveforms, piezoelectric, and EKG tracings were affected by electrocautery for tissue dissection and hemostasis (figure 5). The arterial blood pressure recording was not affected by the signal.

Location of electrocautery in relation to PVP monitor

Bilateral electrocautery grounding pads were placed on the patient's thighs. Electrocautery interfered with the PVP waveform signal to enhance the signal either above or below the baseline waveform (figure6): usage on the ipsilateral side as the Deltran Transducer interfered with the signal causing the waveform to extend below the baseline, while usage on the opposite side as the Deltran transducer enhanced the signal above the baseline. The change from baseline was not seen with EKG or piezoelectric monitoring, only the Figure 6 changes previously discussed.

Motion causes PVP waveform changes

We found that the Deltran pressure transducer was sensitive to small movements directly to the transducer both by the operating staff and anesthesia providers. PVP was also affected by adjusting the height of the operating room table. Moving the operating room table changed the arterial blood pressure monitoring as expected. Other movements such as hitting the bed or adjusting the arterial tubing changed the PVP waveforms. Temporary disruption in the arterial blood pressure recording occurred with blood sampling for arterial blood gas analysis.

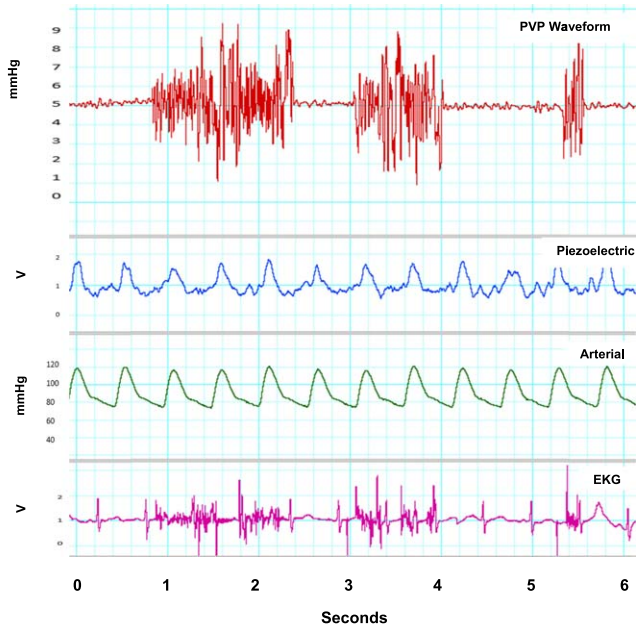

Figure 5. Affect of electrocautery on PVP waveform and EKG. Arterial waveform and piezoelectric monitor are not affected.

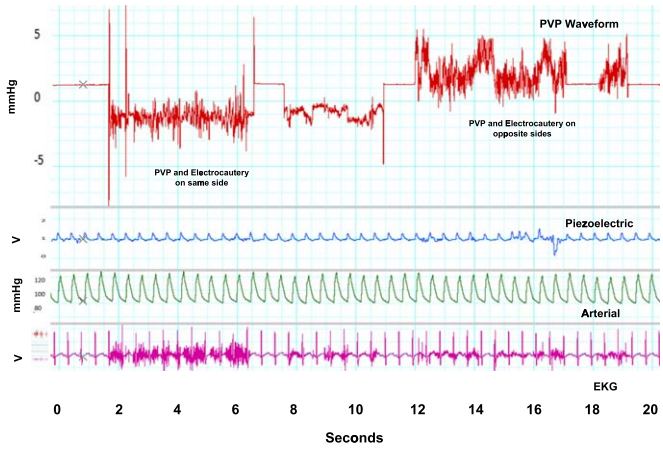

Figure 6. Affect of location of electrocautery relative to PVP waveform pressure. If on same side as PVP waveform, then electrocautery caused an above baseline interference with the signal. If on oppositive side as PVP waveform, then electrocautery caused a below baseline interference with the signal.

Other findings

During dissection of the frontal orbital plate, pressure on the globes can occasionally induce the oculocardiac reflex causing temporary bradycardia and this change was identified on the data acquisition software for the EKG recording. The physiologic change known as the Aschner phenomenon, or oculocardiac reflex, is a peripheral subtype of the trigeminal cardiac reflex, which has been previously described [6].

Location of non-invasive blood pressure cuff during set-up was important. If the cuff was on the same extremity as the PIV for PVP waveform collection, then the waveform was affected during cuff inflation.

Discussion

Our principle finding is that collection of PVP waveforms, piezoelectric monitoring, arterial blood pressure recording, and EKG in a pediatric patient undergoing general anesthesia can be collected prospectively with accurate data acquisition. Pitfalls were encountered during patient monitoring and described in this paper.

Electrocautery is necessary to obtain hemostasis. The electrical current interfered with the collection of PVP waveforms, piezoelectric waveform, and EKG, and hence collecting data during electrocautery use was demonstrated to not be possible. Any data acquired during those brief time intervals has to be

discarded which ranged from 0.7% to 2.1% of the total data collection time.

To decrease the external influence of movement on the Deltran transducer, the length of arterial tubing of 48 inches allowed for Deltran transducer to be taped away from the patient at the foot of the operating table. The location further away allowed for zeroing of the Deltran transducer and securing of the device to decrease external influences. During the course of enrollment, the Deltran transducer was placed next to the arterial blood pressure transducer to control for change in pressure (mmHg) with changing the operating table height.

To obtain relevant PVP waveforms, the location of non-invasive blood pressure cuff was noted. If cuff was on the ipsilateral extremity then the PVP waveforms were inaccurate during the length of cuff inflation.

It has been previously shown that PVP waveforms can be performed in an awake pediatric patient [5]. Results from this pilot study shows that PVP waveform monitoring can be performed in an anesthetized pediatric patient. An ideal modality to determine acute hemorrhage in the pediatric age group would be reproducible, non-invasive, user-independent, and provide a real-time assessment of volume status. This description and utilizing PVP waveforms, piezoelectric waveforms, arterial blood pressure recording, and EKG in pediatric patients could provide a step towards the management of hemorrhage in children and provide a pediatric model to study PVP waveforms during controlled acute hemorrhage.

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