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Study of the entropy as a way to detect venous air embolism using a pre-cordial Doppler

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Abstract

Venous air embolism (VAE) is the air bubble accumulation in the right side of the heart, or in the pulmonary region. Pre-cordial Doppler allows a real-time monitoring of heart sound and is used to detect VAE episodes through changes in cardiac sound. Sometimes these changes are not detected by the operator, which reveals the importance of finding other robust methods for VAE detection. This work aims to study entropy as a feature of the heart sound that may provide useful information on VAE episodes.

A clinical protocol was designed: Doppler Heart Sound (DHS) was collected at baseline, and following infusions of saline with 4 distinct volumes and 2 infusion rates, and given through 2 infusion vias, to 4 patients enrolled in the clinical study. Entropy of these segments was obtained, and relation between the extracted feature and saline infusions was studied.

Entropy presents a good performance showing an increase in response to saline injections (increased blood flow turbulence).

Subject Headings. Medical Research, Neurology, Medical Computing.

Author Keywords. Neurosurgery, Signal Processing, Pre-cordial Doppler, Entropy, Venous Air Embolism.

1. Introduction

Venous Air Embolism (VAE) is a serious complication that may occur during neurosurgical procedures (Law et al., 2012). It is the result of the existence of pressure gradients between the right side of the heart and the incisional area (Albin, 2011).

Both volume and rate of air accumulation are dependent on the size of the vascular lumen as well as the pressure gradient. These factors determine the morbidity and mortality of any episode of VAE, as well as the position of the patient (Palmon et al., 1997; Mirski et al., 2007). On the other hand, pathophysiologic pathways are highly dependent on the volume of gas accumulated within the right ventricle. For high volumes of air accumulation, an outflow obstruction immediately occurs, which can lead to heart failure and cardiovascular collapse. When the volumes of VAE are moderate, signals like hypotension or cerebral ischemia may occur. At the pulmonary level, an entrainment of air may lead to events like bronchoconstriction. VAE symptoms include chest pain, coughing, tachycardia and sense of impending death (Vesely, 2001; Mirski et al., 2007; Albin, 2011; Chan, 1998).

The position of the patient during the surgery may influence the occurrence of VAE events since the pressure differences may facilitate the entry of bubbles in the blood flow. The highest rate of VAE occurrence in neurosurgeries is for the seated posterior fossa surgery

(80%) (McQueen and Shedd, 1998). Neurosurgeries performed in other positions (lateral, supine and prone) have an incidence between 15% and 25% (Palmon et al., 1997).

Since it is not possible to make clinical studies giving air bubbles' infusions, the volumes of gas tolerated by humans are unknown. However, accidental injections of air between 100 ml and 300 ml or 3-5ml/kg resulted in the death of the patients (Law et al., 2012; Palmon et al., 1997; Vesely, 2001; Mirski et al., 2007).

VAE may be difficult to detect because the signs and symptoms associated are not exclusive of this event, and do not always occur (Palmon et al., 1997; Vesely, 2001).

1.1. Detection Methods

Regarding neurosurgeries, each hospital has an anesthesia monitoring protocol that includes the use of monitoring devices, namely to detect VAE episodes. The market allows the assessment of different medical devices for this kind of event, and the choice of the right one to use depends on several factors (medical condition of the patient, expertise of the anesthesiologist, position of the patient during the surgery, among others) (Mirski t al, 2007). However, it is possible to characterize each detection method by its sensitivity, invasiveness and limitations. The adequate selection and use of these devices contribute to an early detection and to a prompt treatment, which can limit the morbidity and mortality of a VAE (Muzzi et al 1990).

Precordial Doppler is one of the most used methods to detect VAE, namely during neurosurgeries, because of its high sensitivity (Palmon et al., 1997; Chan et al., 1997). It was demonstrated that it may detect as little as 0,25ml of air (0,05ml/kg) (Law et al., 2012; Palmon et al., 1997; Mirski et al., 2007).

Regarding its positioning, the Doppler probe is normally placed between the third and sixth intercostal spaces since good results were obtained in adults and children (Palmon et al., 1997; Mirski et al., 2007; Schubert et al., 2006). In order to confirm if the Doppler probe is in the right place (which means that the anesthesiologist may listen to the heart beat clearly), generally an injection of some millimeters of saline fluid is given (Mirski et al., 2007). The result of the saline passing through the right side of the heart can be recognized by a distinct change in the heart sound.

When a VAE occurs, the character and intensity of the emitted sound changes. This change is classically referred to as "a mill-wheel murmur" (Albin, 2011; Palmon et al., 2007). In other words, the sound reflects the turbulent resonance of normal blood flow passing abruptly through the right cardiac chambers.

However, this device presents some weaknesses, namely the inclusion of sound artifacts when the patient is in the prone or lateral positions (Mirski et al., 2007). Another limitation is the absence of air volumes' quantification. This information is mandatory for the anesthesiologist in order to prescribe suitable clinical treatments (Vesely, 2001; Chan et al., 1996).

Detection of the VAE relies on the continuous attention of the anesthesiologist but this may be difficult in long duration neurosurgeries, where the anesthesiologist has to focus his attention in other tasks. Besides this, the surgery room is not a noise-free environment and the presence of noise could mask the existence of changes in the Doppler Heart Sound (DHS).

1.2. Literature Review

In order to understand the sensitivity of a precordial Doppler, and how the DHS may be used to extract information about the air volume entry, Chan et al., (1997) present in the paper

"Fast Detection of Venous Air Embolism in DHS Using Wavelet Transform", a study of qualitative and quantitative properties of the DHS during VAEs. They gave injections of known volumes of air in the vessels of dogs and extract spectral characteristics of the embolic heart sound (EHS), using the Wavelet Transform (WT). The main conclusions of this work are that WT of DHS provides a fast detection and accurate volume assessment of the embolic air. However, the use of bandpass filters and of just one cut-off frequency may hide details in high frequency components and in the estimation of correct volumes of embolic air. The authors also proved that this new algorithm only takes a mean of 8 ms to process one heartbeat, demonstrating that it may be useful for on-line applications. This work was later expanded in "A Real-Time Monitor using Wavelet Analysis of the Doppler Heart Sound for the Detection of Venous Air Embolism" (Chan et al., 1997) where a real-time monitor to detect VAE was developed using the Borland C++ program.

This work aims to continue the previous study in (Tedim et al, 2014), where some features were extracted from the Doppler heart sound before and after infusions of saline at different rates and volumes of entry, with results indicating that the entropy was the feature with best results in blood flow turbulence detection (75% of saline injections were detected).

2. Materials and Methods

In order to have comparable results, this work mimicked the previous methodology. Patients enrolled in this study were submitted to total intravenous anesthesia (TIVA), a widely used anesthetic technique, where general anesthesia is given by an intravenous line (Eikaas and Raeder, 2009). Propofol and remifentanil were the hypnotic and analgesic drugs, respectively.

2.1. Data Acquisition

Data was collected after institutional approval by the Department of Education, Training and Research, Ethics Committee, and Administration Board of the Santo António's Hospital, Centro Hospitalar do Porto. Patient that filled the inclusion criteria and signed the written informed consent were enrolled in the study.

The precordial Doppler Hadeco, model Smartdop 45©, was placed on the patient's chest (Palmon et al., 1997; Mirski et al., 2007; Schubert et al, 2006). The injection of air bubbles is not possible ethically so infusions of saline were given as a way to mimic changes in the DHS. 16 saline injections, with intervals of 15 seconds, at volumes 1, 5, 8, and 10 ml, and at two administration rates (slow and fast), were given by peripheral and central catheters to each patient (always by the same anesthesiologist).

Clinical data was collected using the software RuglloopII Waves, including the data obtained through the precordial Doppler. DHS was collected at 8 kHz and the researcher annotated the time of each infusion.

2.2. Data Processing

MATLAB 2012 was used for signal processing. Frames of 3 s were analyzed and pre-processing included signal filtering and the application of the Butterworth low pass filter with a cut-off frequency of 1800 kHz in two different directions and the DHSs downsampling to 2 kHz. A Savitzky-Golay filter (Savitzky and Golay, 1964) was used to smooth the signal with the same previous constrains.

Then, the energy of the signal was extracted using windows of 0,5 s (corresponding to one cardiac event) and detected peaks were used to create a smooth envelope of the signal that shows the changes in amplitude of the signal, as can be seen in Figure 1.

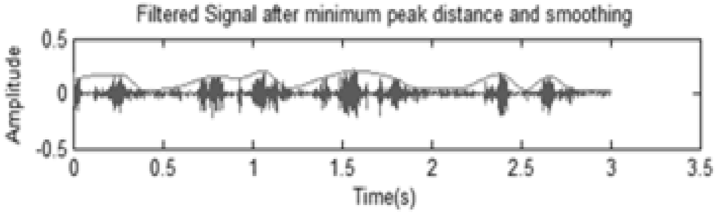

Figure 1: Envelope of the DHS Signal

The generated envelopes were used to calculate cross-correlations between two consecutive frames, as can be seen in Figure 2.

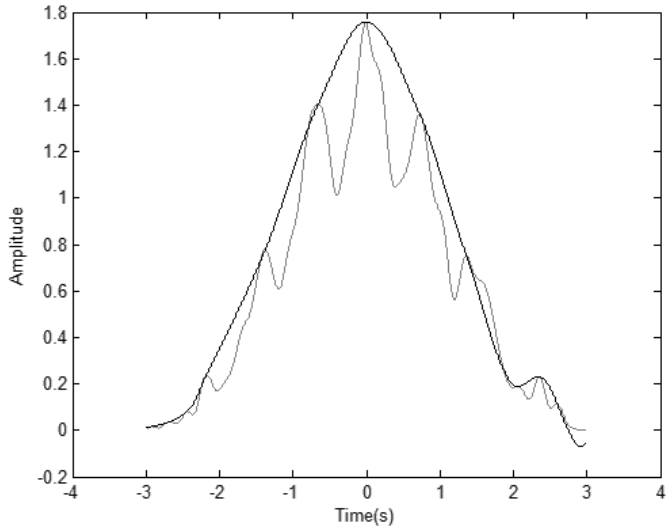

Figure 2: Cross-correlation between two consecutive frames of the energy envelope

Then, the local maximums were detected and the distance between the 1st and 2nd peaks, was used to calculate the cardiac cycle and consequently, the heart rate of each patient.

Shannon Entropy (E) was calculated for segments of 0,1s. The mean for the heartbeats during two seconds after the infusions of saline was stored in a vector.

Entropy values were stored in a text file and exported to a spreadsheet The Entropy average value for each injection and patient was calculated. Graphical representations relating infusion volumes with administration rates for the two different vias are presented.

3. Results and Discussion

Four patients were enrolled in this study. All acquisitions where made in females (means: age=73 years; height=159 cm; heart rate=75 beats/min; weight=62 kg).

To evaluate turbulence episodes, the average value of the E of the DHS events in the 2 s following injections were analyzed, for each injection, for each patient. Feature values were normalized by the observed baseline value, meaning the ratio between features post-injection and baseline feature, in terms of percentage. Figure 3 shows the results obtained for this feature for different infusion volumes, for two rates and distinct catheters of administration.

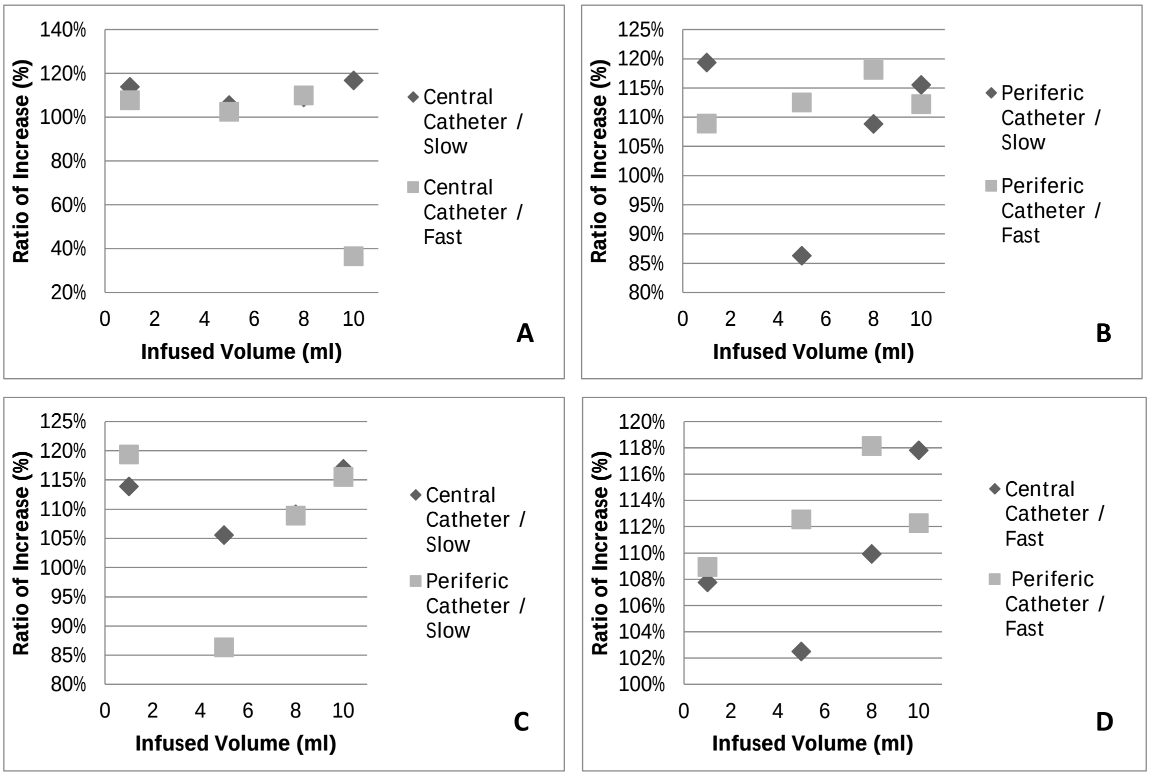

Figure 3: Relation between the infusion volume and the rate of increase (%) of E for A) slow and fast velocities of saline infusion via central catheter; B) slow and fast velocities of saline infusion via peripheral catheter; C) slow infusion of saline via central and peripheral catheter; D) fast infusion of saline via central and peripheral catheter

Figure 3A) and 3B) show that the infusions with higher rates tend to cause more audible turbulences. However figures 3C) and 3D) show that the turbulence was equivalent for both catheters (central and peripheral) which it is not in accordance with the rational that turbulence is more easily detectable for central catheter. More acquisitions will be necessary to validate these results.

Nevertheless, E shows to be consistent to detect episodes of turbulence once almost all values are superior to baseline values (ratio of increase superior to 100%).

We should highlight that the number of patients is reduced since to be enrolled the study requirements needed to be fulfilled, which limited the number of acquisitions.

4. Conclusions

VAE is a problematic event that consists in the accumulation of air bubbles on the right side of the heart, causing several health problems when is not detected in time, including death. In order to prevent these episodes, it is important to know how VAE occurs and what methods can be applied and enhanced.

Mimicking VAE episodes by infusion of saline was, at this time, the best way of obtain turbulence events in the heart in an innocuous way. The use of different infusion volumes, and catheters for administration allows to understand their impact on the detection of embolic venous events.

Regarding the results obtained in this study, a high variability was observed because the number of patients was reduced. Nonetheless, DHS entropy changes were observed for almost all saline infusions.

As future work, the number of acquisitions should be increased in order to reduce the variability of the results.

Another important step will be to acquire Doppler heart sounds when VAE events occur, and correlate them with the results showed in this paper and in the previous studies. In this way, it will be possible to establish a entropy threshold, and to test, and enhance it when a VAE occurs.

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