Software-based Prediction of Cannula Occlusion during Extracorporeal Blood Circulation through Networked Medical Data

André Stollenwerk[1,*], Jan Kühn[1], Marian Walter[2], Christian Brendle[2], Nabil Wardeh[3], Rolf Rossaint[3], Steffen Leonhardt[2], Stefan Kowalewski[1], Rüdger Kopp[3]

[1]Informatik 11 - Embedded Software, [2]Philips Chair for Medical Information Technology, both RWTH Aachen University, 52056 Aachen
[3]Clinic for Anesthesiology, RWTH Aachen University Clinic, 52056 Aachen
[*]corresponding author: stollenwerk@embedded.rwth-aachen.de

Abstract

This paper presents a novel method to predict the occlusion of a withdrawing cannula during extracorporeal circulation due to a networked intensive care setup. During in-vivo experiments we were able to detect the cannula suction up to 90 seconds prior to the collapse of extracorporeal blood flow. The elaborated metric is based on heart rate, extracorporeal blood flow and blood pressure at the withdrawing cannula conjoined in a cyber-medical system.

1 Introduction

Intensive Care Units (ICU) develop towards an increasingly complex composition of medical devices. In order to optimize the treatment of a life threatening condition a high number of different medical devices is used to monitor and control the vital signs. However, still the devices are only sparsely interconnected to each other [GBF12].

Thereby ICU treatments get more and more invasive and a higher need for functional safety arises. One possible new dimension in overcoming this drawback is the joint analysis of connected sensors in order to derive additional safety relevant information. By utilizing these cyber-medical systems new therapies are available for critically ill patients.

In a variety of ICU-established therapies the patient's blood is treated outside the human body. This form of treatment is usually used to support the patient's circulation (e.g. dialysis, extracorporeal membrane oxygenation (ECMO), ventricular assist devices (VAD)). One of the possible hazards during such a treatment is the occlusion of the sucking cannula by the withdrawing vessels wall [SAM+12, HRB+04].

1.1 Worked Example

This paper focuses on the detection of the collapse of a blood vessel during an extracorporeal circulation (EC). The drawn blood vessel may collapse if blood is actively sucked from the human body. Subsequently the collapsing vessels' wall can obstruct successively the holes of the drawing cannula. This results in a rapid breakdown of the extracorporeal circulation. In clinical applications the EC has currently to be stopped after a cannula occlusion.

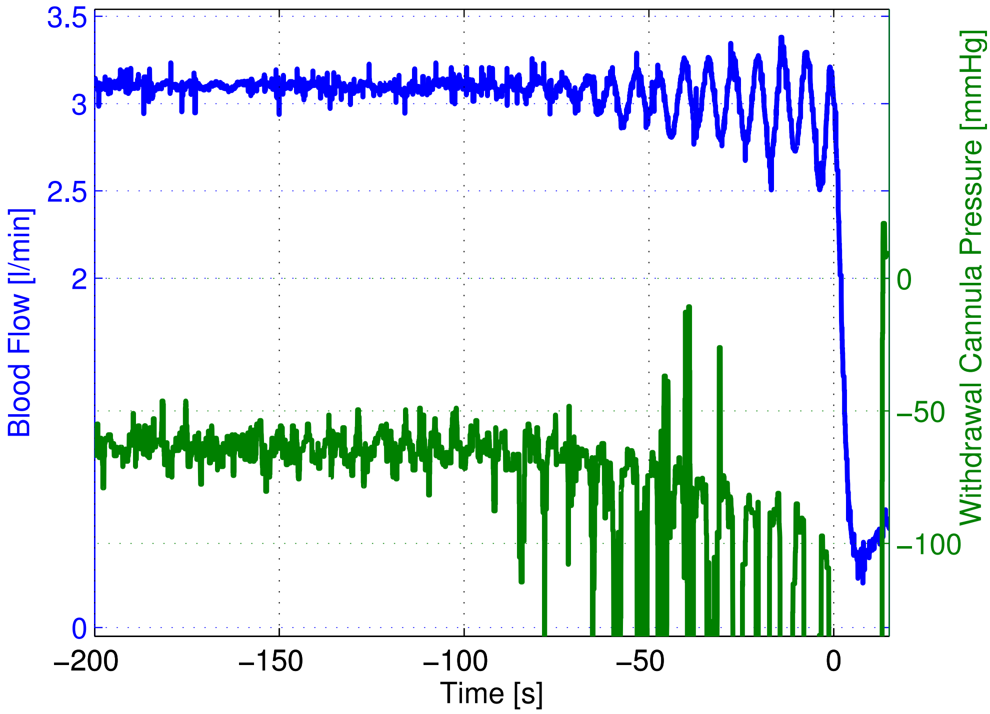

Figure 1: Blood flow and pressure prior to the occlusion of a vessel to the withdrawing cannula

Following the EC can be reestablished after a calming phase of some seconds (with no extracorporeal blood flow). Hence the patient's extracorporeal support can no longer be ensured.

Due to our introduced cyber-medical system architecture of sensors and actuators [SGW+11] we were enabled to predict the occlusion of the blood withdrawing cannula.

2 Extracorporeal Circulation

Several therapies in intensive care medicine are based on EC. All these methods have in common that the extracorporeal blood flow is preset [PCR+13]. The resulting extracorporeal blood flow (Q_{ext}) and the blood pressure at the point of withdrawing and reinsertion (p_w and p_r) is usually measured. In an ICU these values are not available on a focused device in general. Therefore we introduced an embedded safety network [SWW+09], which interconnects all sensors and actuators in the medical setup. Thus, every node within this network to know all measurement values and set points, respectively.

Cannula occlusion may be caused by e.g. dislocation of the dawning cannula within the vasculature or hypovolemia due to dehydration [SAM+12]. If a vessel's wall occludes the withdrawing cannula and the extracorporeal blood flow collapses, the EC has to be stopped, before it can be reestablished. Subsequently the vasculature needs time to refill the vessel. Afterwards the EC can be restarted and slowly increased.

Based on the analysis of the data of cannula occlusion occurrences a model was establishes, which enables the prediction of cannula occlusion within a horizon of 50 to 90 seconds. Figure 1 shows the blood flow Q_{ext} through the EC and the pressure at the withdrawing cannula p_w. Q_{ext} collapses at the timestamp 0 s and can only be reestablished by stopping the pump. The first peaks in the signal can be observed about 90 seconds prior to the collapse. For reasons of vividness the plotted blood flow signal is low-pass filtered. In the following we will elaborate the measure used to predict the cannula occlusion and comment on our implementation.

3 Base Conditions for Cannula Occlusion Detection

The presented work bases on the setup of a veno-venous ECMO, which was applied to pigs ($m \approx 55\,\mathrm{kg}$) in animal experiments. Blood is taken from the vena cava inferior, by a DP2 blood pump (Medos, Stolberg, Germany), passed through a Medos Hilite 7000 Oxygenator and returned into the vena jugularis externa (see Figure 2).

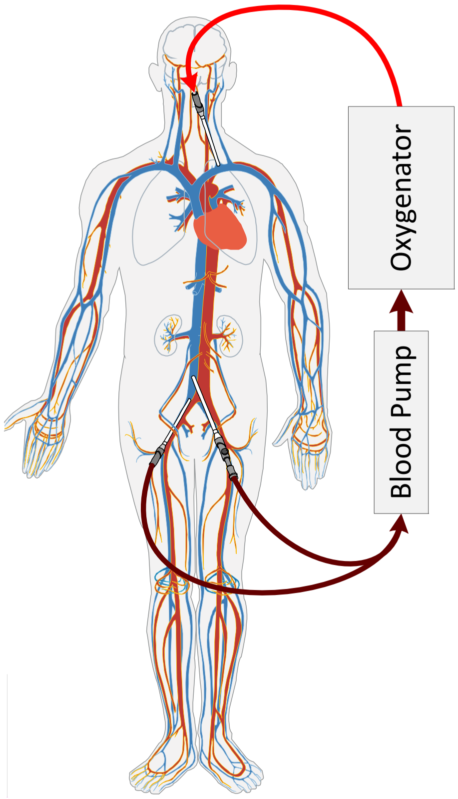

Figure 2: Cannulization and setup of ECMO therapy

The withdrawing branch of the cannulization is a twofold design in order to reduce the risk of cannula occlusion. Nevertheless the previously described problem still exists. In this setup in general a slight pulsation of the tubing can be observed prior to an occlusion of the cannula to the surrounding vessel.

The used rotary blood pump was driven by a self-developed console specific for this application. The original manufacturer's restrictions with respect to the pump interfaces enforced a proprietary development. The pump can be operated as a revolution speed controlled device or as a blood flow controlled device, respectively. In the latter case a blood flow sensor has to be introduced to the setup and connected to the network. For this purpose a flow sensor model HT 110 with an HQ9XL sensor probe (Transonic Systems ultrasonic, Ithaca, NY, USA) was used. For measuring the pressure at the withdrawing cannula a piezoelectric pressure sensor (Smiths Medical, Ashford, Kent, UK) were introduced to the setup, which also feed in the embedded safety network. These two sensor readings are analyzed.

3.1 Extracorporeal Blood Flow

The blood flow through the EC (Q_{ext}) shows an oscillation before the blood flow collapses. This oscillation reflects the pulsation of the tubing. In order to quantize this oscillation we calculated the Fourier transform of Q_{ext}. Figure 3 shows the spectrum of Q_{ext} according to Figure 1 as well as a plot of the maximum of the logarithmic power spectral density $E_{\text{max,log}}$ of the signal. In the spectrum an increased energy can in general be observed at the heart rate and the respective multiples. In this case the heart rate of the patient was approximately 70 bpm. At the same time the constant component is noisy. Hence a filter which attenuates the constant component and the pulse is applied.

The preprocessed signal can be used to calculate the energy of the corrected flow signal. In Figure 3 a significant increase of spectral energy ($\text{E}_{\text{max.log}}$) can be recognized. Therefore we conclude that this event can be detected about 80 to 90 seconds before the EC has to be stopped (at $t = 0\,\text{s}$).

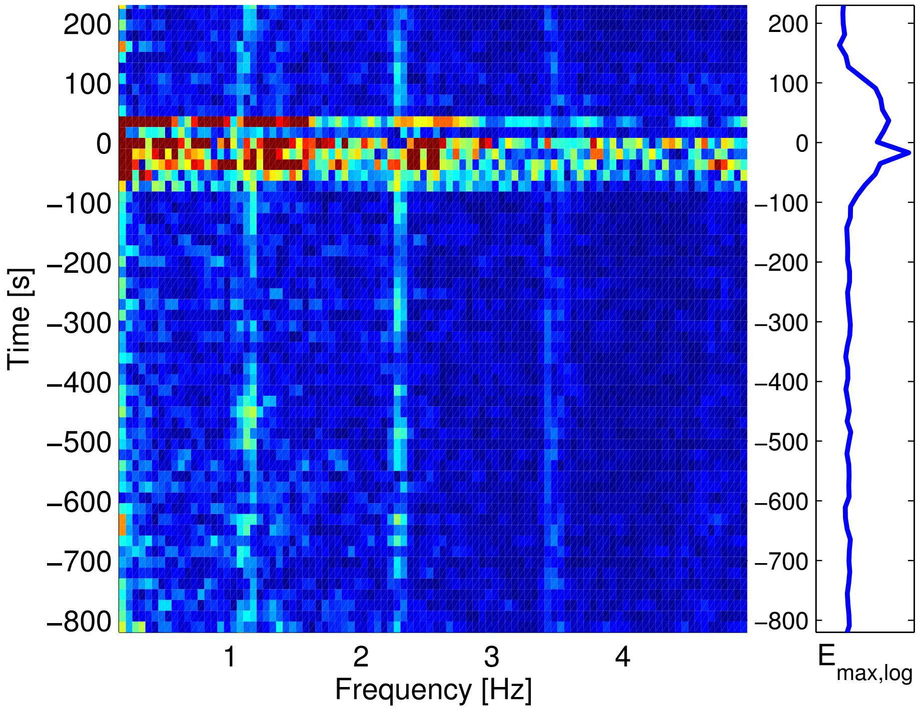

Figure 3: Spectrum and maximum of power spectral density of the blood flow signal

3.2 Withdrawing Pressure

The blood pressure measured at the withdrawing cannula p_w will lead to a comparable spectrum like presented in the previous section. In general the pressure difference over a pipe and the resulting blood flow (if it is a laminar flow) are linked via the Hagen-Poiseuille equation:

$$\frac{dV}{dt} = \frac{\pi \cdot r^4 \cdot \Delta p}{8 \cdot \eta \cdot l}. \tag{1}$$

Where V is the flow, Δp the resulting pressure difference over the length l of a pipe with the radius r and η is the dynamic viscosity of the moved fluid. In this worked example the Hagen-Poiseuille equation cannot be utilized due to underconstrained parameters. Blood is a shear thinning (non-Newtonian) fluid hence there is no fix dynamic viscosity η [HB59]. In addition the tubing of the EC and above all the geometric properties of the patients' vasculature are not known in detail. Therefore no direct relation between the extracorporeal blood flow and the withdrawing pressure can be given.

In the worked example the utilized pressure sensor has a less significant dynamic compared to the blood flow sensor. Hence the spectrum of the blood flow signal offers information with a higher resolution. Nevertheless the blood pressure signal offered valuable information and redundancy with respect to functional safety. If one of the sensors fails in operation we still can analyse a reduced information set, that allows prediction of cannula suction.

Considered from the physical way a blood vessel can only collapse if there is no positive pressure within the vessel. In addition the likelihood of collapsing increases in proportion to the negative p_w. Therefore the whole model is only calculated if $p_w < 0$. In addition the smaller the p_w and the higher the variance of p_w the higher the probability of cannula occlusion is assumed.

4 Implementation

The introduced algorithm was implemented in C on the embedded safety network. Due to the existing software architecture [SGW$^+$11] the calculation can be embedded to any of the nodes or be moved between them respectively.

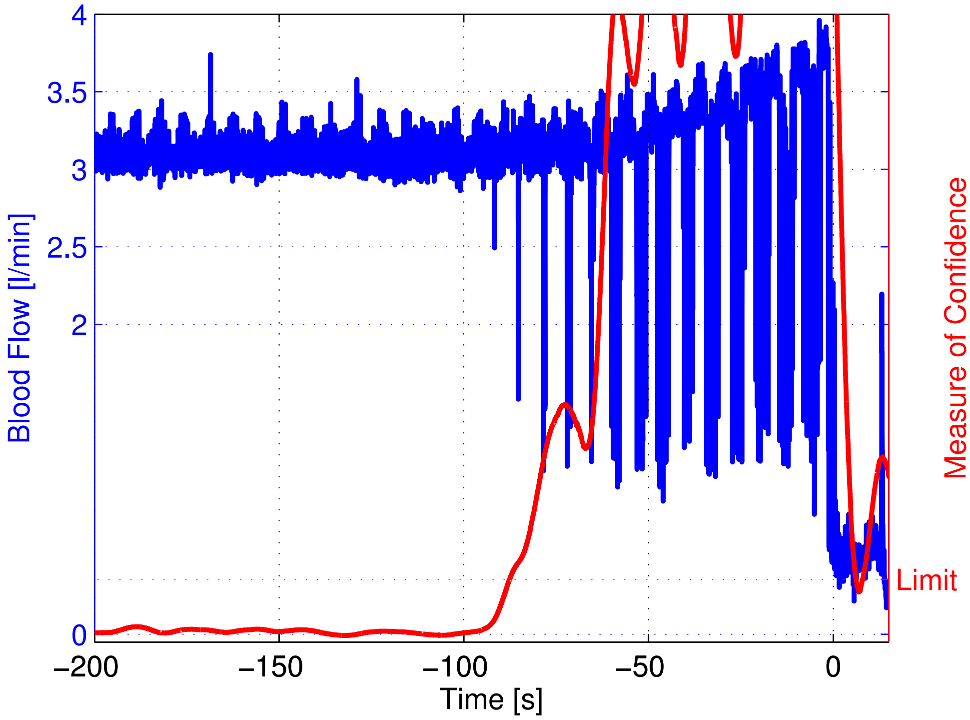

Figure 4: Extracorporeal blood flow and calculated measure of confidence for the occlusion of the withdrawing cannula

The analysis as introduced in Section 3.1 needs information about the current pulse, which is feed into the network by a patients monitor (datex ohmeda AS/3). Both presented measures of confidence from the previous sections 3.1 and 3.2 are summed up. The measure of confidence for the introduced example is plotted in Figure 4. In this case the occlusion of the dawning cannula is predicted 87 seconds before the blood flow collapses.

5 Evaluation

The presented algorithm's design is based on five events of cannula occlusion, which encountered during about 153 hours of animal experiments. These animal experiments were conducted in order to develop a safe closed loop control for extracorporeal lung assist therapy [SWW+09]. During this research the clinically known problem of cannula occlusion witnessed. Hence we investigated on a software-based prediction of this hazard.

The limit for the measure of confidence to predict the cannula occlusion was empirically determined in a way that there are no false positives in the animal experiment data. Hence all events could be detected. A retrospective analysis shows that this metric can be used as indicator for hypovolemia.

We also tried to introduce an animal model for the occlusion of a withdrawing cannula. Unfortunately it was not possible to develop a model with stable and reproducible behavior.

6 Conclusion

This paper presents an approach to predict the occlusion of a withdrawing cannula by a blood vessel's wall during an extracorporeal blood circulation. The occlusion can be predicted up to 90 seconds in advance. This does not only prevent the patient from possible harm, but also allows new therapies to confide on extracorporeal circulation. The presented measure of confidence for the cannula occlusion is another step towards a safer cyber intensive care unit. Further investigations will have to show the general robustness of this method und applicability to different types of blood pumps.

7 Outlook

The presented work settles on a data base of five events. Therefore it should be refined with a larger base. This could be achieved on the one hand by evaluating a lager EC data set or on the other hand by establishing a reproducible and stable animal model for cannula occlusion.

The evaluation showed that the introduced metric can be used as an indicator for hypovolemia. The proceeding investigations shall elaborate the according potential and limits.

Acknowledgements

This work was supported by the German Research Foundation DFG (DFG - Grant PAK 138/2). The authors gratefully acknowledge this allowance.

References

[GBF12] David Gregorczyk, Timm Bubhaus, and Stefan Fischer. A proof of concept for medical device integration using web services. In *9th International Multi-Conference on Systems, Signals and Devices (SSD)*, pages 1–6, 2012.

[HB59] Robert H. Haynes and Alan C. Burton. Role of the non-Newtonian behavior of blood in hemodynamics. *American Journal of Physiology – Legacy Content*, 197(5):943–950, 1959.

[HRB+04] Mark R. Hemmila, Stephen A. Rowe, Tamer N. Boules, Judiann Miskulin, John W. McGillicuddy, Douglas J. Schuerer, Jonathan W. Haft, Fresca Swaniker, Saman Arbabi, Ronald B. Hirschl, and Robert H. Bartlett. Extracorporeal life support for severe acute respiratory distress syndrome in adults. *Annuals of Surgery*, 240(4):595–605; discussion 605–7, Oct 2004.

[PCR+13] Matthew L. Paden, Steven A. Conrad, Peter T. Rycus, Ravi R. Thiagarajan, and ELSO Registry. Extracorporeal life support organization registry report 2012. *ASAIO J*, 59(3):202–210, 2013.

[SAM+12] David Sidebotham, Sara J. Allen, Alastair McGeorge, Nathan Ibbott, and Timothy Willcox. Venovenous extracorporeal membrane oxygenation in adults: practical aspects of circuits, cannulae, and procedures. *Journal of cardiothoracic and vascular anesthesia*, 26(5):893–909, 2012.

[SGW+11] André Stollenwerk, Florian Göbe, Marian Walter, Tobias Wartzek, Rüdger Kopp, Jutta Arens, and Stefan Kowalewski. Smart data provisioning for model-based generated code in an intensive care application. In *High Confidence Medical Devices, Software, and Systems & Medical Device Plug-and-Play Interoperability (HCMDSS/MDPnP 2011), Chicago, USA*, 2011.

[SWW+09] André Stollenwerk, Marian Walter, Tobias Wartzek, Rüdger Kopp, Jutta Arens, and Stefan Kowalewski. A safety and control concept for extracorporeal membrane oxygenation. *The international Journal of Artificial Organs*, 32(7):428, September 2009.