Open Access

Philipp Stark*, Christoph Kalkbrenner, Patrick Braß and Rainer Brucher

Artificial blood circulatory and special Ultrasound Doppler probes for detecting and sizing gaseous embolism

DOI 10.1515/cdbme-2016-0062

Abstract: This paper presents a special designed artificial blood circulatory (ABC) for studying gaseous embolism based on detection of gaseous emboli and their sizing using ultrasound (US) spectral Doppler. Blood mimicking fluid (BMF) was used in the circulatory to get valid results without using human blood. The additional necessary degassing circulatory shows a promising effect of decontaminating the BMF from air bubbles. This offers the base for detecting and sizing microemboli using special algorithms and finally leads to reliable calculations of dangerous embolism and its air volume. Standard US probes at an integrated tissue model and a new 8-MHz central catheter ultrasound (CCUS) probe inside a superior vena cava model (SVCM) are used and deliver the Doppler spectrogram as input for automatic emboli detection and further signal analysis. First results using the newly developed 8-MHz CCUS probe inside the SVCM and its Doppler spectrogram characteristics show promising results but need more detailed studies.

Keywords: air bubble contamination; air embolism; artificial blood circulatory; central venous catheter; doppler ultrasound; embolus detection; microemboli.

1 Introduction

In up to 80% of all brain surgeries in sitting position gaseous emboli occur [1]. The air which is sucked into the venous blood stream by hydrostatic effects can reach the arterial bloodstream via the patent foramen ovale (PFO) which occurs in up to 35% of people [2]. Such collected air volumes up to 2–3 ml in the cerebral blood circulatory can be a lethal amount as well as 0.5–1.0 ml of air in the vena pulmonalis can lead to myocardial infarction [3]. The ability to detect, to characterize and to size intraoperative occurring emboli and at last their aspiration via catheter may have a great potential for patients safety. Two methods of automatic detection and discrimination between solid and gaseous microemboli based on transcranial Doppler ultrasound (TCD) have shown success, the dual-frequency technique [4, 5] and the frequency modulation method [6, 7]. These methods however use Doppler probes outside the body and are only able to detect emboli and cannot offer any treatments by removing gaseous emboli by aspiration.

The aim of this study was to assess by *in vitro* studies the specially designed ABC as well as the first ultrasound Doppler central venous catheter system that was specially developed for the automatic detection of intraoperative emboli inside the superior vena cava.

***Corresponding author: Philipp Stark,** Faculty of Medical Engineering, Hochschule Ulm, University of Applied Sciences, Prittwitzstraße 10, 89075 Ulm, Germany, E-mail: stark@hs-ulm.de
Christoph Kalkbrenner and Rainer Brucher: Faculty of Medical Engineering, Hochschule Ulm, University of Applied Sciences, Prittwitzstraße 10, 89075 Ulm, Germany, E-mail: kalkbrenner@hs-ulm.de (C. Kalkbrenner), brucher@hs-ulm.de (R. Brucher)
Patrick Braß: Helios Klinikum, Krefeld Klinik für Anästhesie Intensivmedizin und Schmerztherapie, Lutherplatz 1, 47800 Krefeld, Germany

2 Material and methods

2.1 Development of the artificial blood circulatory

The developed artificial blood circulatory (ABC) is designed to represent the human blood circulatory including a SVCM for the *in vitro* experiments. The ABC consists of two parts, the large main blood circulatory and an additional small degassing circulatory (see Figure 1). The whole ABC holds up to 1.2 liter of blood mimicking fluid (BMF). The ABC is driven by the membrane pump (*SUK-0220*, *SHURflo*). To generate different flow profiles with a flow up to 2.4 l/min a control unit by hard- and software was build up using Labview.

The BMF recipe was taken from EN 61685:2001 D.3.3 (see Table 1). This BMF shows the same properties as blood with a hematocrit value of 42% to 48% (see Table 2).

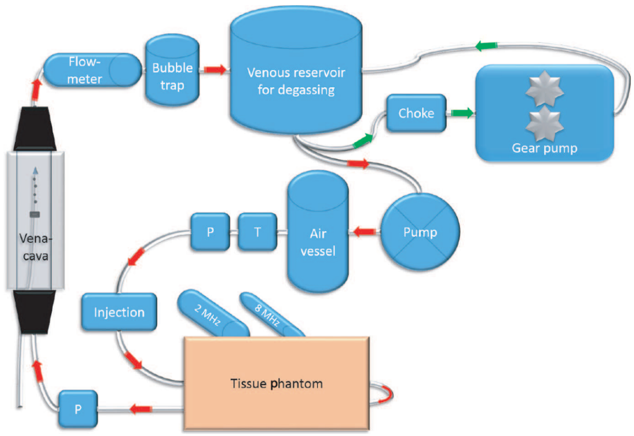

Figure 1: Artificial blood circulatory: Main circulatory with tissue phantom and the Vena Cava model (red arrows), additional degassing circulatory with implemented gear pump for low pressure degassing (green arrows).

Table 1: Components of BMF in weight % of pure components

Water	83.86%
Glycerol	10.06%
Dextran (molecular weight 150 kDa)	3.36%
Orgasol-particel 5 µm	1.82%
Synperonic N.	0.09%

Table 2: BMF properties

c	1548 m/s
ρ	1037 kg/m^3
Z	$1.61 \cdot 10^6 6$ kg/(m^2 s)
ν	4,0 mPa s

The SVCM consists of an inlet, outlet and was designed for a laminar flow with a Reynolds number of $Re = 122.37 << Re_{krit} = 2320$ as stated in [8] to avoid warping of the velocity profile. The SVCM was manufactured out of polycarbonate which has a similar acoustic impedance as blood vessel walls.

It is of the utmost importance for the results of the experiments and the development of algorithms that the BMF is not contaminated with microbubbles. Analyzing the echogenity of air embolism on its enhancement in Doppler spectrogram would result in false estimations if the BMF is contaminated by microbubbles. To decontaminate the fluid the degassing circulatory was added to the ABC. It consists of a choke and a special gear pump (Fresenius Medical Care) (see Figure 2). The degassing process is done by generating a low pressure. Low pressure conglomerates the dissolved gas and forms larger bubbles which rise up to the surface of the fluid in the venous reservoir and disappear out of the main circulatory.

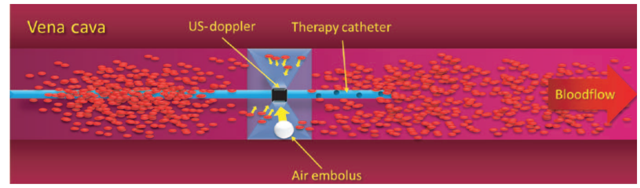

Figure 2: Central catheter ultrasound probe (CCUS): Intravascular positioning recording passing air embolus by radial insonation. Therapeutical air aspiration located on the top end of the catheter.

The injection of the gaseous emboli is done manually using calibrated high precision microliter syringes (Carl Roth) with a grading down to 0.1 µl.

The BMF is monitored via three US probes. The 2-MHz TCD-probe and 8-MHz hand-held probe, are used as control recordings and as a reference for the distal integrated 8-MHz CCUS probe (MTB Medizintechnik Basler AG), which has to be optimized in future experiments. The two references probes are located right after the injection spot on top of the US tissue model (MiniSim Trainer, Life-Tech, Inc.) insonating via a 45° angle. The 8-MHz catheter probe is positioned via a medical port into the SVCM and has a radial insonation. The audio signals from the US reference probes are processed by our own system (FHU Lab-Dop) and its corresponding software for spectral Doppler. The signals of the 8-MHz catheter probe is processed by the DWL Doppler-BoxX and its corresponding QL software offering a spectral and a Power-M-Mode Doppler.

To monitor the ABC in respect to the volume rate a flowmeter (B.I.O-TECH e.K.) as well as specially designed pressure and temperature sensors are integrated into the circulatory to register the physical effects on the injected gaseous embolism. For data acquisition a module (NI USB-6008, National Instruments) and Labview software was integrated. Both pumps are controlled via this module. The main pump resembles the heart and offers a continuous or a pulsatile flow profile. The pulsatile flow can be varied on three parameters: heartrate, overall flow ejection and the duration of the systole.

3 Results

3.1 2/8-MHz reference ultrasound probes

Figure 3 shows the pulsatile flow profile. Multiple air bubble events are detected by the 2-MHz Spectral Doppler instrumentation analyzing the enhancement of the short-term events in the Doppler spectrogram caused by resonance effects. In opposite the signals recorded by the 8-MHz Doppler show no events. Here the effect of low pass

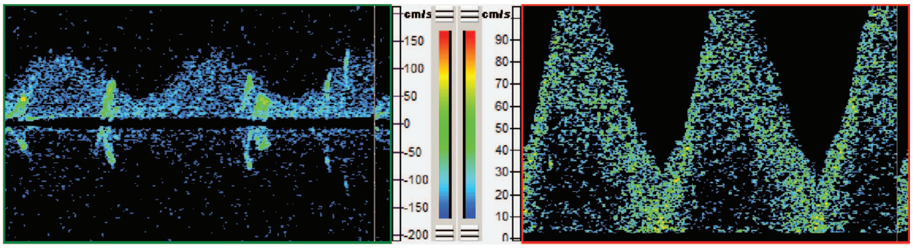

Figure 3: 2-MHz (left) and 8-MHz (right) Doppler spectrogram showing pulsatile flow profile enhancements caused by air bubble injection.

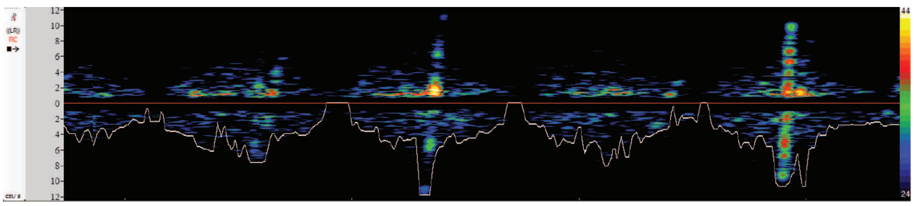

Figure 4: 8-MHz CCUS probe spectral Doppler recording of passing bubbles during pulsatile flow profile.

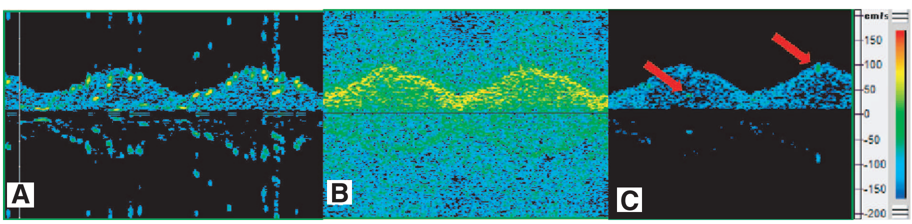

Figure 5: 2-MHz-spectrogram showing flow profile (A) before degassing. Circulatory is contaminated due to microbubbles from former experiments or due to natural dissolved gas, (B) during degassing with a typical strong enhancement due to the large number of microbubbles like contrast agents, (C) after degassing shows single sporadic microbubble event (red arrow).

filtering of the insonated 8-MHz US suppress the expected enhancement.

3.2 8-MHz ultrasound catheter probe

Figure 4 shows air bubble events, detected by the intravascular positioned 8-MHz CCUS probe recording the enhancements of the bubbles due to higher embolus/blood ratios within the SVCM compared to 8-MHz reference recording in tissue model. The 8-MHz CCUS Doppler records a characteristic spectrogram during passing embolus. Here the bottom part of the spectrogram shows towards flow to the US probe. The mid part close to the zero line shows no Doppler effect. The top part of the spectrogram shows the flow away from the probe. Therefore the event of passing by of the air bubbles shows time sequentially the according Doppler shift frequencies.

3.3 Degassing

Figure 5A shows a 2-MHz spectrogram of the BMF before degassing. In the Doppler spectrogram events of microbubbles are present in parallel to the normal background flow profile. These gas bubbles originate either from former experiments or the natural dissolved gas in the liquid. The simultaneous positive and negative Doppler effects during microbubbles events are due to overload and reduced channel separation.

Figure 5B shows a 2-MHz-spectrogram during degassing signal of the BMF. Compared to the pre-degassing-condition an overall enhanced signal can be observed. Here the whole system is flooded with microbubbles like during injection of contrast agent.

Figure 5C shows the 2-MHz-spectrogram after one hour of degassing and a couple of minutes of settling time to get rid of the last bubbles. Afterwards the Dopper spectrogram shows only neglect able events gas bubbles in the ABC.

4 Discussion and conclusion

Air bubble event detected by the 8-MHz CCUS probe (see Figure 4) shows time sequentially an enhancement at

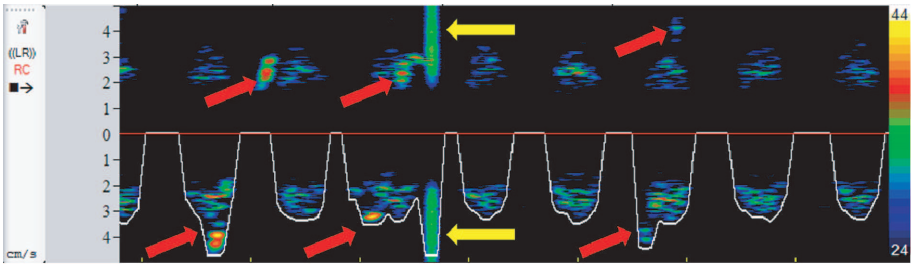

Figure 6: 8-MHz CCUS probe spectrogram with enhancements due to air bubble events (red arrows) and an artefact (yellow arrows).

Doppler shifted frequencies according the variation of the Doppler effect due to insonation angle. This time delay of enhancement in forward and backward Doppler shift frequencies is a characteristic for all detected air bubble events recorded by the CCUS probe. In opposite an artefact shows simultaneous enhancement in the upper and lower part of the spectrogram (see Figure 6). Therefore an air bubble can be distinguished from an artefact based on these different characteristics.

During the degassing process the whole ABC system is flooded with microbubbles (see Figure 5b). This is due to the procedure in the degassing circulatory connected in parallel to the main circulatory. To decontaminate the BMF a pressure difference is generated via the gear pump and a choke on the inlet of the degassing circulatory. Since the degassing circulatory and the ABC work simultaneously the generated bubbles spread into the main circulatory. The signal is almost free of embolic events after one hour of degassing followed by a settling time of a few minutes (see Figure 5C). During the settling phase all the generated bubbles are trapped in fluidic filters (100 µm) and the venous reservoir. Based on this tremendous reduction of microembolic events the analysis of enhancements leads to reliably results for detection and size estimation of the overall volume of the detected microbubbles.

Based on these first results the ABC is a very promising design for *in vitro* studies using the newly designed 8-MHz CCUS probe and its optimization. The ABC is able to degas contaminated fluids in an easy way in an acceptable short amount of time. It also allows to operate in continuous and pulsatile flow profiles. The variation of pulsatile flow profile offers the setting to all natural blood flow characteristics and to study the requirements for reliable air bubble detection and their volume calculation. The newly designed 8-MHz CCUS probe shows promising results and characteristics for automatic detection of embolic events. Therefore further future experiments using this SVCM might lead to the improvement of the central venous catheter ultrasound probe including finally automatic triggered aspiration of air embolism in respect to its application of therapy.

Acknowledgment: The authors would like to thank Compumedics Germany GmbH for their hardware, assistance and support.

Author's Statement

Research funding: This study is part of the project entitled "EmboKath" in cooperation with Compumedics Germany GmbH supported by the Arbeitsgemeinschaft industrieller Forschungsvereinigungen AiF (KF2186206KJ4). Conflict of interest: Authors state no conflict of interest. Material and methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

References

[1] Wenham TN, Graham D. Venous gas embolism: an unusual complication of laparoscopic cholecystectomy. J Minim Access Surg. 2009;5:35–36.
[2] Fisher DC, Fisher EA, Budd JH, Rosen SE, Goldman ME. The incidence of patent foramen ovale in 1,000 consecutive patients. Chest. 1995;107:1504–9.
[3] Ho AM. Is emergency thoracotomy always the most appropriate immediate intervention for systemic air embolism after lung trauma. Chest. 1999;116:234–7.
[4] Brucher R, Russell D. Automatic online embolus detection and artifact rejection with the first multifrequency transcranial doppler. Stroke. 2002;33:1969–74.
[5] Russell D, Brucher R. Online automatic discrimination between solid and gaseous cerebral microemboli with the first multifrequency transcranial doppler. Stroke. 2002;33:1975–80.
[6] Girault JM, Kouamé D, Ménigot S, Souchon G, Tranquart F. Analysis of index modulation in microembolic doppler signals part i: radiation force as a new hypothesis—simulations. Ultrasound Med Biol. 2011;37:87–101.
[7] Smith JL, Evans DH, Naylor AR. Analysis of the frequency modulation present in doppler ultrasound signals may allow differentiation between particulate and gaseous cerebral emboli. Ultrasound Med Biol. 1997;23:727–34.
[8] Sigloch H. Technische fluidmechanik. Berlin, Heidelberg: Springer Berlin Heidelberg; 2012.