Medical Engineering & Physics 36 (2014) 981–990

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Automation of a portable extracorporeal circulatory support system with adaptive fuzzy controllers

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ARTICLE INFO

Article history:
Received 12 May 2013
Received in revised form 16 April 2014
Accepted 26 April 2014

Keywords:
Fuzzy control
Control
Extracorporeal circulation
Cardiovascular modelling
Adaptive control
Extracorporeal support system
Haemodynamic simulation
Gas exchange modelling

ABSTRACT

The presented work relates to the procedure followed for the automation of a portable extracorporeal circulatory support system. Such a device may help increase the chances of survival after suffering from cardiogenic shock outside the hospital, additionally a controller can provide of optimal organ perfusion, while reducing the workload of the operator.

Animal experiments were carried out for the acquisition of haemodynamic behaviour of the body under extracorporeal circulation. A mathematical model was constructed based on the experimental data, including a cardiovascular model, gas exchange and the administration of medication. As the base of the controller fuzzy logic was used allowing the easy integration of knowledge from trained perfusionists, an adaptive mechanism was included to adapt to the patient's individual response. Initial simulations show the effectiveness of the controller and the improvements of perfusion after adaptation.

1. Introduction

Cardiogenic shock caused by myocardial infarction is associated with a mortality of more than 60% [1]. Early treatment of patients having low cardiac output or during prolonged cardiopulmonary resuscitation (CPR) could be prevented from multi-organ failure with the use of an extracorporeal support system (ECSS) reducing this high mortality rate [2–4].

Since its first successful use in 1953, cardiopulmonary bypass (CPB) has been established as the gold standard for maintaining circulatory and pulmonary function in patients undergoing cardiac surgery [5,6]. Throughout the past decade, CPB has been introduced into cases of emergency circulatory resuscitation in patients with cardiogenic shock.

The use of CPB systems in emergency situations is often limited by the large size and complicated setup of currently available systems [3]. Recently a variety of portable devices have become available for the treatment of patients suffering from cardiogenic shock outside the cardiac surgery unit. These devices are operated by trained medical staff rather than by perfusionists.

To reduce the workload of the operator in a hectic scenario, and allow the safe transportation of patients to the hospital a complete automated perfusion system guided by an adaptive and robust control system is desirable. This paper describes the development of such control system for the automation of Lifebridge B2T, an already available portable extracorporeal circulatory support system (ECSS) [7,8].

Previous attempts to automate an extracorporeal support system have been performed by Misgeld et al. [9] and Meyrowitz [10]. Their studies focused on the automation of normal heart–lung machines (HLM) more commonly used in the operating room. These types of machines use rotary pumps and are not suitable for transportation. Misgeld proposed a proportional–integral (PI) and a robust type of controller and Meyrowitz presented a model predictive controller. This paper focuses on the automation of the more portable ECSS, which compared to the conventional HLMs uses a centrifugal pump to generate blood flow and is connected through femoral cannulation.

The proposed automation is based on fuzzy logic, allowing the easy integration of the expert's knowledge with the creation of

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http://dx.doi.org/10.1016/j.medengphy.2014.04.009
1350-4533/

control rules. Previous research has focused on creating a multiple input–single output adaptive mechanism that can change the controller's rules based on a reference model and the response of the system. This was shown to work effectively for adjusting the pressure and flow of an in vitro system consisting of a pump and a reservoir acting as a compliance element [11]. This control mechanism was extended for this work to create a multiple input–multiple output automation system capable of adjusting flow, pressure, oxygen saturation and medication. For the development of the controller an animal model was used to obtain haemodynamic characteristics similar to patients under extracorporeal circulation (ECC). A mathematical model was constructed from the animal model and was used for extensive evaluations and validation of the controller.

2. Methods

2.1. Animal model

Domestic pigs were used in the animal model for the acquisition of haemodynamic parameters during ECC. The experiments were approved by the Bavarian authorities, and the animals received humane care in compliance with Guide for the Care and Use of Laboratory Animals (NIH publication 85-23).

Four domestic pigs weighing 50 ± 0.7 kg were pre-medicated with an intramuscular injection of ketamine (15, Ketanest®, Parke Davis, Munich, Germany) and an atropine sulphate injection (0.5, Braun, Melsungen, Germany). General anaesthesia was induced by intravenous injection of propofol (60–100 mg, propofol, Lipuro, B.Braun Ag, Melsungen, Germany). Anaesthesia was maintained by continuous intravenous application of propofol (10 mg/kg/h propofol 2%) and fentanyl (30 μg/kg/h, fentanyl, Jannsen Cilag, Neuss, Germany) through a syringe pump. After endotracheal intubation, the pigs were placed on a respirator and ventilated with a mixture of oxygen and air. The fraction of inspired oxygen (FiO_2) was set on 0.5. A catheter was inserted into the jugular vein (ArrowHowes™ Quad-Lumen central venous catheter, Arrow International Inc., USA) for monitoring of the central venous pressure (CVP). Through the right femoral artery, a catheter tip manometer (Millar MIKRO-TIP® SPC350, Houston, TX, USA) was placed in the descending aorta for monitoring the aortic pressure. Median sternotomy was done and the pericardium was opened. To measure the aortic flow, a perivascular ultrasonic flow probe (A-Serie, Transonic Systems Inc., Ithaca, NY, USA) was placed at the descending aorta above the crossing of the pulmonary veins. Another flow probe (C-Serie, Transonic Systems Inc., Ithaca, NY, USA) was placed in the ascending aorta. Connection with the ECSS was done through femoral cannulation. From the arterial side a 20 F arterial cannula (Medtronic, Inc., Minneapolis, MN, USA) was introduced into the femoral artery and a 22 F cannula (Edwards Lifesciences, CA, USA) was placed in the femoral vein (Fig. 1).

For the acquisition of gas exchange information a CDI 500 gas analyser was used with a sampling rate of 1 sample every 6 s (Terumo Medical Corp, Tokyo, Japan). The sensors were placed

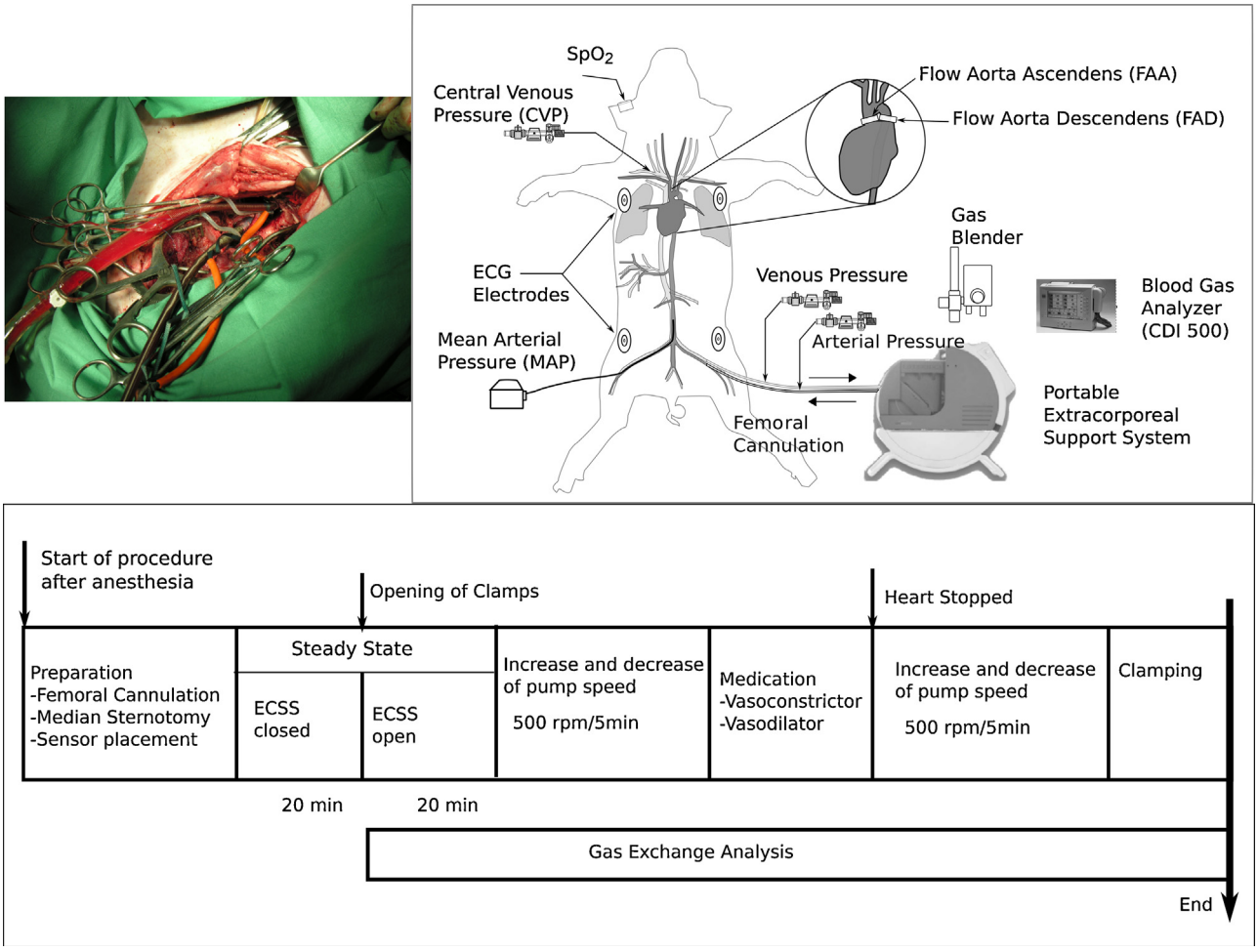

Fig. 1. Experimental setup and procedure.