Artificial Intelligence in Medicine (2009) **45**, 35—52

ARTIFICIAL INTELLIGENCE IN MEDICINE

http://www.intl.elsevierhealth.com/journals/aiim

A hybrid hierarchical decision support system for cardiac surgical intensive care patients. Part I: Physiological modelling and decision support system design

Mouloud A. Denaï [a], Mahdi Mahfouf [a,*], Jonathan J. Ross [b]

[a] *Department of Automatic Control & Systems Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom*
[b] *Northern General Hospital, Sheffield S5 7AU, United Kingdom*

Received 29 December 2007; received in revised form 2 September 2008; accepted 6 November 2008

KEYWORDS
Cardiac intensive care unit;
Cardiovascular system model;
Hemodynamics;
Cardiovascular drugs;
Clinical decision support system;
Fuzzy control;
Genetic algorithms

Summary

Objective: To develop a clinical decision support system (CDSS) that models the different levels of the clinician's decision-making strategies when controlling post cardiac surgery patients weaned from cardio pulmonary bypass.
Methods: A clinical trial was conducted to define and elucidate an expert anesthetists' decision pathway utilised in controlling this patient population. This data and derived knowledge were used to elicit a decision-making model. The structural framework of the decision-making model is hierarchical, clearly defined, and dynamic. The decision levels are linked to five important components of the cardiovascular physiology in turn, i.e. the systolic blood pressure (SBP), central venous pressure (CVP), systemic vascular resistance (SVR), cardiac output (CO), and heart rate (HR). Progress down the hierarchy is dependent upon the normalisation of each physiological parameter to a value pre-selected by the clinician via fluid, chronotropes or inotropes. Since interventions at each and every level cause changes and disturbances in the other components, the proposed decision support model continuously refers back decision outcomes back to the SBP which is considered to be the overriding supervisory safety component in this hierarchical decision structure. The decision model was then translated into a computerised decision support system prototype and comprehensively tested on a physiological model of the human cardiovascular system. This model was able to reproduce conditions experienced by post-operative cardiac surgery patients including hypertension, hypovolemia, vasodilation and the systemic inflammatory response syndrome (SIRS).

* Corresponding author. Tel.: +44 114 222 5607; fax: +44 114 222 5624.
E-mail address: m.mahfouf@shef.ac.uk (M. Mahfouf).

doi:10.1016/j.artmed.2008.11.009

Results: In all the simulated patients scenarios considered the CDSS was able to initiate similar therapeutic interventions to that of the expert, and as a result, was also able to control the hemodynamic parameters to the prescribed target values.

1. Introduction

Cardiac surgery on cardio-pulmonary bypass (CBP) is associated with various physiological changes that profoundly alter a patient's hemodynamic status. They can include hypotension (low blood pressure) arising from hypovolemia, blood loss, dysrhythmias, arterial vasodilation, and pump failure from myocardial dysfunction [1,2]. These can present themselves clinically in isolation, arise together, develop sequentially, or even consequent upon another pathophysiological process. For example, hypovolemia causing arterial hypotension will reduce myocardial perfusion resulting in a poorer cardiac contractility. This would manifest as sequential and possible exponentially worsening drop in blood pressure which may not be fully reversed by restoration of the depleted circulating fluid volumes. Conversely, hypertension (elevated arterial blood pressures) may arise from a re-vascularised and therefore better-perfused heart which pumps more vigorously, from a stress response arising from pain, from insufficient sedation, or from poorly controlled pre-existing hypertension. A patient, with hypotension immediately after an operation secondary to myocardial stunning from CPB, may recover within hours and develop hypertension during weaning from ventilatory support. Therefore, a successful clinical decision support system (CDSS) must be flexible in its implementation of advisory support, and be robust enough to interpret apparently contradictory responses to its outputs, and take into account the potential changes arising extraneously in the target system.

One approach to controlling this complex environment is to reduce the cardiovascular system to a set of physiological components which are maintained at prescribed targets, and any deviations from the desired set-points are corrected promptly by drug administration and fluid therapy. The authors selected the systolic blood pressure (SBP), central venous pressure (CVP), systemic vascular resistance (SVR), cardiac output (CO) and heart rate (HR) as such physiological components. The decision model based on these interacting hemodynamic components of the cardiovascular system is well-defined, hierarchically structured and can be prioritised in different sequences, if required, to adapt to a wide range of intensive care patients. In our population we maintained the prioritisation in the above order for all cases.

Many cardiac surgery units prioritize systolic blood pressure (rather than the mean arterial pressure (MAP)) as the over-riding clinically relevant parameter as systemic hypotension leads to poorer myocardial perfusion, poorer myocardial function and low cardiac output, and can precipitate the failure (by vasospasm) of arterial grafts used in the coronary artery bypass grafting surgery. This can be life-threatening. Also, hypertension can disrupt suture lines or cause delicate tissues in the heart and aorta to fail.

Post-operatively, these high-risk patients require close monitoring and judicious therapeutic decisions to avert complications which may have repercussions upon the length of patient hospital stay, costs, and the quality of life.

The complexity of this decision-making task poses a significant challenge to healthcare personnel who need to interpret many data-streams of real-time information generated from a proliferation of bedside monitoring devices, make rapid decisions and intervene promptly to reestablish the optimum function of the patient's vital organs. This control environment constitutes an appealing field for a computerised CDSS application as a systematic means to overcome the stark disjunctions in clinicians' choices of therapies.

There has been substantial evidence of the effectiveness of CDSS in improving the quality, safety and efficiency of healthcare delivery and many CDSSs are now in routine use in clinical care settings, clinical laboratories, incorporated in electronic medical record systems and in educational institutions [3—5]. CDSSs have been shown to be particularly useful in prescribing medication by providing alerts and reminders to possible drug interaction or incorrect drug dosage, in diagnostic assistance and in therapy critiquing and planning [6,7]. In the critical care arena, CDSS research activities have focussed mainly on diagnosis [8—11] and therapy advice [12,13]. The implementation approaches range from simple decision trees, truth tables and rule-based systems to more complex paradigms such as those associated with neural networks, fuzzy reasoning, Bayesian statistics and machine learning theories which have the ability to model the inherently uncertain medical domain knowledge and learn