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Principles of pharmacologic hemodynamic management and closed-loop systems

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Every day, physicians in critical-care settings are challenged with the hemodynamic management of patients with severe cardiovascular derangements. There is a potential role for closed-loop (automated) systems to assist clinicians in managing these patients and growing interest in the possible applications. In this review, we discuss the basic principles of critical-care hemodynamic management and the closed-loop systems that have been developed to help in this setting.

Introduction

Every day, physicians in critical-care settings are challenged with the hemodynamic management of patients with severe cardiovascular derangements. Generally speaking, hemodynamic management involves the optimization of blood and oxygen delivery to the tissues and, if done well, has been shown to improve postoperative outcomes and decrease surgical costs [1]. There is a potential role for closed-loop (automated) systems to assist clinicians in managing these patients and growing interest in the possible applications.

A closed loop is a system in which a controller monitors one or more system variables and delivers one or more interventions to control that system in response, based on a predetermined algorithm. Closed-loop systems are actually quite prevalent in everyday life; ovens that automatically maintain an internal temperature based on a user-entered setting are a simple example. Closed loops have proven stable and consistent in providing reliable services to humans in all scopes of life. Closed-loop control in the field of

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medicine remains fairly rare, however, due to regulatory challenges, safety, the intricacies of biological systems, imprecise measurement methodologies, and physician acceptance [2]. Nevertheless, closed-loop systems have the potential to be powerful medical tools. A well-designed automated controller can facilitate previously manual tasks and improve stability and accuracy of the controlled variables. Furthermore, the implemented algorithm is perfectly repeatable, meaning it can be continuously tested and improved upon. An example of a closed-loop vasopressor system is depicted in Fig. 1.

Oxygen delivery depends on both adequate tissue perfusion pressure (mean arterial pressure or MAP), to drive blood into the capillaries of all organs, and adequate cardiac output (CO), to ensure necessary oxygenation and nutrient delivery while removing metabolic waste from tissues [3]. We will review both of these factors separately in Sections Co management and Blood pressure management before discussing specific hemodynamic variables and closed-loop control in Section Closed-loop hemodynamic management.

Co management

Numerous studies have demonstrated that CO optimization during high-risk surgery results in improved postoperative outcome with associated savings in costs [4–6]. However, CO monitoring is rarely used in daily anesthesiology practice and clinicians still rely primarily on personal judgment, blood loss estimates, and the relatively vague concept of interstitial compartment losses [7]. Nevertheless, with the increasing availability of minimally invasive and noninvasive CO monitors, this trend is changing and CO optimization is now formally recommended by many health services for moderate-to high-risk surgery [8].

We have long known that both hypovolemia and hypervolemia are undesirable conditions that increase morbidity and mortality. When a patient is hypovolemic, intravenous (IV) fluid administration can increase CO by expanding intravascular volume and thereby increasing venous return to the heart. However, depending on the existing cardiac preload and where the heart is operating on the Starling curve, additional fluid may not increase CO but only contribute the fluid third spacing. Additionally, the relationship between CO and arterial pressure is not fixed, making blood pressure monitoring alone an inadequate surrogate for evaluation of the effectiveness of a fluid bolus in improving overall hemodynamics. Nonetheless, the standard practice of fluid administration in the clinical setting has focused heavily on arterial pressure alone, while CO monitoring is, more often than not, overlooked.

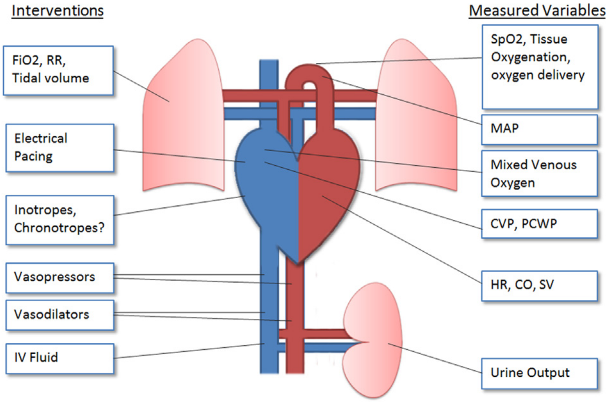

Fig. 1. Example Closed-Loop Vasopressor System. A closed-loop system is simply some form of automated intervention. All closed-loop systems have three essential components – a *monitor* that measures the variables of interest, a *controller* that transforms the measurements into an action, and an *intervention* that somehow affects the system being controlled. In this case, a waveform is recorded from an arterial line by a pressure transducer (the monitor). The measurement is transferred to the controller, which uses an internal algorithm to determine what action to take based on the measurement. The action is then sent to the intervention (in this case, an infusion pump delivering a vasopressor) in order to increase, decrease, or maintain the current therapy as appropriate. The monitor, controller, and intervention may all be combined in a single physical device or may exist as a distributed system across multiple physical components.