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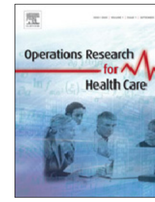

A framework to accelerate simulation studies of hyperacute stroke systems

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HIGHLIGHTS

- We define a domain specific modelling framework for decision support in stroke.
- Domain specific frameworks improve reuse and efficiency of studies.
- We define the requirements for a domain specific conceptual modelling framework.
- We propose an extended framework for endovascular therapy.
- We illustrate the use of the framework with a real world example.

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ABSTRACT

Stroke care has been identified as an area where operations research has great potential. In recent years there has been a small but sustained stream of discrete-event simulation case studies in modelling hyperacute stroke systems. The nature of such case studies has led to a fragmented knowledge base and high entry cost to stroke modelling research. Two common issues have faced researchers in stroke care: understanding the logistics and clinical aspects of stroke care and moving from these findings to an appropriately detailed model. We aim to accelerate studies in this area by introducing a conceptual modelling framework that is domain specific for stroke. A *domain specific framework* trades-off the wide applicability of a general framework against increased efficiency and reuse to support modelling in the problem domain. This compromise is appropriate when the problem domain is complex, of high value to society, and where the saving in future modelling effort is likely to be greater than the effort to create the framework. We detail the requirements of a domain specific conceptual model and then provide domain specific knowledge to support modellers in gaining an understanding of the problem situation, translating this knowledge into selected model outputs, inputs and content in the case of hyperacute stroke. We illustrate the use of the framework with an example based at a large hospital in the United Kingdom.

1. Introduction

The inaugural issue of Operations Research for Healthcare identified stroke care as an area where operations research had the opportunity to do much better [1]. In the years following this call to action, there have been a small number of discrete-event simulation (DES) studies focused on the logistics of hyperacute stroke care (e.g., [2–4]). This includes a special issue on stroke within this very journal (e.g,. [5,6]). The case study approach taken by these studies and the varying levels of detail that are found within the reporting of simulation studies [7] has resulted in a fragmented knowledge base. Researchers have no structured advice to assist in the diagnosis of logistical issues facing stroke services or indeed how to move beyond these findings and conceptualise an appropriately detailed model. As such the researcher entry cost to this complex domain of health has remained high.

Conceptual modelling (CM) is the process of identifying what to model and what not to model [8,9]. A CM *framework* is a set of specific steps that guide a modeller through the development of a

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conceptual model [10]. Current CM frameworks for simulation are highly generalisable. These are applicable to broad classes of systems such as healthcare [11], supply chains [12] and defence [13]; or operations systems in general [10]. The broad nature of these frameworks is both a strength and a weakness. Generic frameworks lack domain specific knowledge on system characteristics to improve both the quality and efficiency of model building. As such they do little to lower the entry cost of researchers into a new complex domain such as stroke. A *domain specific* CM framework is limited in application to a single domain, such as a particular disease treatment pathway, and is reusable across different studies that tackle problems in that domain. Such frameworks lower the entry cost to a new domain by adding domain specific knowledge to a simulation study. For example, details of system elements, relationships, and solutions.

This article details a reusable *domain specific* CM framework for DES to support investigation of how pre-hospital and intra-hospital logistics affect patient outcomes in hyperacute stroke pathways (HASPs). The treatment problem our framework addresses is large scale, applying internationally with an estimated fifteen million strokes occurring worldwide per year. It is widely acknowledged in the stroke literature that there are large gains in treatment rates and favourable patient outcomes through better organisation of stroke care services. However, traditional healthcare evaluation designs such as Randomised Controlled Trials (RCTs) are failing to make an impact [14,15], while simulation studies have led to a fourfold increase in treatment rates of the real system [6]. Internationally there is an urgent need to set up and optimise many similar HASPs.

Our work therefore provides four contributions. First we derive the requirements of a domain specific framework. Second we provide modellers of HASPs with a common knowledge to efficiently develop their simulation models, thereby seeking to exploit similarities observed in stroke system set-up and the choice of simulation model components. We primarily focus on intravenous thrombolysis although we introduce potential ways to model recent intra-arterial therapy advancements in Section 4.4. Third we illustrate the use of the framework using a real world case example. Last, our CM framework is highly reusable in modelling studies of HASPs and mitigates the technical challenges of model reuse at the coding level.

The remainder of the paper is organised as follows. Firstly we provide the background to treatment of acute stroke. This is followed by a review of simulation and conceptual modelling for stroke care. We then present our domain specific CM framework. We detail steps to understand the problem, set modelling objectives and select model content. The framework is then illustrated using a case study from the UK. The final section discusses the implications of the framework and future work.

2. Background

2.1. Stroke

Stroke is major cause of disability internationally and accounts for approximately 1 in every 9 deaths worldwide [16]. The world health organisation estimates that fifteen million people suffer a stroke each year. The cost of stroke is estimated to be 2%–4% of total healthcare costs worldwide [1]. To reduce the substantial human and economic burdens of stroke, healthcare systems must be responsive to the emergency an acute stroke represents [17].

Stroke is categorised into two types: ischaemic and haemorrhagic. The majority of strokes are ischaemic (∼85%), occurring when blood flow to part of the brain is interrupted due to blockage of an artery by a thrombus (blood clot). The latter type refers to a bleed within the brain.

Stroke treatment pathways can be thought of having three distinct phases: the hyperacute (emergency), the acute and the rehabilitation. The stroke pathway is typically initiated by someone other than the patient who witnesses the onset of stroke or finds a patient with suspected stroke. In this article we focus on conceptual modelling for HASPs — the most time critical phase with respect to treatment options and health outcomes and represents up to the first 4.5 h following symptom onset [18]. Treatment of patients in the hyperacute phase is associated with high direct and indirect cost savings in follow-up phases [19–21].

2.2. Hyperacute stroke pathways

The hyperacute pathway is focused on identification and treatment of stroke patients suffering an ischaemic stroke. It aims to treat a patient using recombinant tissue plasminogen activator (tPA) within 4.5 h of the onset of symptoms potentially combined with endovascular therapy (EVT) within 6 h of onset. Both tPA and EVT restore blood flow to the affected region of the patient's brain either, by dissolving or mechanically retrieving the clot, respectively. Each minute saved in time to treatment prevents loss of 2 million brain cells and adds over a day of extra healthy life on average [22].

EVT is a recent advancement in stroke treatment, that holds much promise, but is not yet widely available due to constraints in terms of workforce capacity and expertise, and dedicated equipment being available 24/7. As such, tPA remains the dominant treatment. Worldwide use of tPA in stroke lies between 1%–8% [23,24]. This low performance is partly attributable to the limited window of opportunity, i.e., the period of time available for rescuing brain tissue while a sequence of events must occur; each of which are vulnerable to delays. A patient or witness must recognise stroke symptoms, contact emergency medical services (EMS), travel to the hospital, be assessed and then be processed in emergency and radiology departments. Fig. 1 provides an overview of a hyperacute pathway. Critical parts of the pathway are often considered to be the recognition of stroke symptoms, the speed at which EMS are contacted and the availability of a Computed Tomography (CT) scanner to rule out haemorrhagic stroke.

Although there are inherent difficulties in successful implementation of HASPs, there is international evidence that operations can be optimised to treat large numbers of ischaemic stroke patients. For example, hyperacute centralisation in London, [25], intra-hospital process improvement programmes in Finland [26] and Australia [27], and optimised 'chain-wide' communication in Chicago [28].

3. Simulation of hyperacute pathways

3.1. Simulation studies

In recent years there have been several pioneering modelling studies that have focused on improvement of the HASP or aspects of it. All have applied DES [2,4,5,29–33]. Table 1 lists the focus of these studies along with the inputs and decision variables explored. There is a significant overlap in all of these studies. For example, all apart from [4] have included some elements of intra-hospital operations such as delays in brain scanning or availability of resources. These studies evaluated alternative pre-hospital and intra-hospital processes in terms of their impact on cycle time targets, treatment rates and post stroke disability. For example, analysing a 'scoop and run' protocol where the patient is transferred to the hospital with minimal pre-hospital work-up by ambulance personnel [2]; or analysing alternative intra-hospital procedures to ensure patients undergo CT scanning within set time limits [32].