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Implementation strategies of a contract-based MRI examination reservation process for stroke patients

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ABSTRACT

Timely imaging examinations are critical for stroke patients due to the potential life threat. We have proposed a contract-based Magnetic Resonance Imaging (MRI) reservation process [1] in order to reduce their waiting time for MRI examinations. Contracted time slots (CTS) are especially reserved for Neural Vascular Department (NVD) treating stroke patients. Patients either wait in a CTS queue for such time slots or are directed to Regular Time Slot (RTS) reservation. This strategy creates "unlucky" patients having to wait for lengthy RTS reservation. This paper proposes and analyzes other contract implementation strategies called RTS reservation strategies. These strategies reserve RTS for NVD but do not direct patients to regular reservations. Patients all wait in the same queue and are served by either CTS or RTS on a FIFO (First In First Out) basis. We prove that RTS reservation strategies are able to reduce the unused time slots and patient waiting time. Extensive numerical results are presented to show the benefits of RTS reservation and to compare various RTS reservation strategies.

1. Introduction

This paper is motivated by our collaboration with a large French university teaching hospital in order to reduce the waiting time of stroke patients treated in Neural Vascular Department (NVD). A stroke is the sudden loss of brain function, which is usually caused by interruption of the blood supply (ischemic stroke) and rupture of a blood vessel (hemorrhagic stroke). The brain is deprived of oxygen and nerve cell death will occur in the area of the brain with no blood flow. The patients will suffer from severe physical and cognitive deficits. It is crucial for stroke patients to have timely imaging examinations in order to have appropriate diagnosis and treatment.

However, significant delays are observed because many key examinations rely on expensive and heavily used imaging facilities such as Magnetic Resonance Imaging (MRI). In France, the average waiting time for MRI examinations is about 30–40 days. Stroke patients, just like the other routine patients, have to reserve the time slots via fax or via telephone for the emergency patients. Long waiting time has a negative impact on quality of care and patient service [2].

In order to reduce the waiting time of stroke patients, we proposed in [1] a contract-based MRI examination reservation process. The imaging department managing the MRI facilities reserve each week some Contracted Time Slots (CTS) for NVD treating stroke patients. Stroke patients can be served by either CTS or regular time slots (RTS) in case of arrival surges of stroke patients. CTS decisions and RTS assignment policy determine the efficiency of the reservation process. The former is the number of CTS and its distribution over the time, whereas the latter refers to the policy for assigning incoming patients to RTS. We proposed a method combining stochastic programming model and Markov Decision Process (MDP) to simultaneously determine the two decisions. Structural properties of the optimal RTS assignment policy were established by an average cost MDP model. It is proved that there exists a threshold L_i for each day i and the optimal RTS assignment control consists in sending patients to RTS by keeping CTS queue length below L_i. Then Monte Carlo approximation and local improvement were used to determine CTS decisions and RTS assignment policy. Computational results showed that the reservation process can greatly reduce the average waiting time of stroke patients. However, there exist some "unlucky" patients who are directed to RTS and have to wait much longer time than those who wait for CTS.

In order to solve this problem, this paper proposes three new MRI reservation processes. In these processes, RTS is reserved for NVD and added to the list of CTS. CTS and RTS time slots are grouped according to their day of availability and filled by patients. No patient is directed to wait for lengthy RTS. All patients wait in

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the same queue for MRI time slots and are scheduled to either CTS or RTS in a FIFO (First In First Out) order and according to the release dates of CTS and RTS.

Three RTS reservation policies are proposed in this paper based on patient queue length information and some service ratio criterion. We first prove that RTS reservation policies outperform RTS assignment policy with shorter patient waiting time and less unused MRI time slots. We then perform extensive numerical experiments to compare the performances of different contract implementation strategies.

The rest of this paper is organized as follows. Literature review is described in Section 2. Section 3 defines and compares different MRI-contract implementation strategies. Formal proofs that RTS reservation strategies improve RTS assignment strategy are given in Appendix A. Section 4 presents computational results to show the efficiency of RTS reservation strategies and the impact of different problem parameters. Conclusions and perspectives are given in Section 5.

2. Literature review

Capacity reservation and scheduling of imaging facilities, such as computer tomography (CT) and MRI scanners, have received limited coverage. The two earliest contributions are [3,4]. Simulation was used in [3] to investigate the effect of scheduling rules on patient waiting time and physician idle time for X-rays in a chest radiology department. It was demonstrated in [4] that more technicians and orderlies do not imply better service quality. To improve the radiology services, the emphasis was the design of the management systems and scheduling techniques.

A new scheduling method was proposed in [2] to identify improvement potentials in order to reduce MRI access time. Finite-horizon dynamic program was used in [5] to effectively allocate the expensive imaging diagnosis capacity among several classes of patients during a day. Properties of the optimal policies are identified in order to design the outpatient appointment schedule, and establish dynamic priority rules for admitting patients into services. [6] proposed a simple approach for dividing the available diagnosis capacity between emergency and inpatients on the one hand and outpatients on the other. MDP was used in [7] for the admission of multi-priority patients on a waiting queue to a diagnostic resource. An approximate dynamic programming approach was proposed to overcome the state space explosion problem. The same problem was solved in [8] with protection level policies by protecting a part of the capacity from the lower priority jobs in order to make it available for the future higher priority jobs. A perturbation analysis technique was proposed to evaluate sample-path gradients with respect to the protection levels. A stochastic approximation approach was used to determine the optimal protection levels.

MDP was used in [9] to allocate two CT-scanners to three patient groups with different arrival patterns and different cost-structures in order to maximize the total expected reward. Ref. [10] determined the optimal number of outpatients to schedule and the assignment of outpatients to a variable-block/fixed-interval appointment schedule. An MDP approach was proposed in [11] to decide whether to accept requests for MRI examinations from patients with different priorities such as inpatients and outpatients. Different examination types, cancelations, no-shows and over-booking, and same-day demand were considered. A continuous-time Markov decision process was used in [12] to model the problem of accepting or rejecting the reservation of different services by different classes of customers. The solution strategy was proposed by using simulation-based approximate dynamic programming (ADP) combined with a discrete event simulation of the service period. Numerical experiments show that the heuristic ADP algorithm performs very well in terms of objective function value, solution time, and memory requirements.

Queueing theory was used in [13] to determine the number of schedule slots to open in a radiology department for urgent CT and ultrasonography in order to keep the rescheduling rate of routine studies to accommodate emergencies below a certain level. Ref. [14] examined a multi-period capacity allocation model with upgrading by considering multiple product types and multiple classes of demand. The optimal allocation policy was shown to be a simple two-step algorithm: meet demands with available capacity of the same-class, and then upgrade customers until a protection limit of a class-dependent capacity. Bounds of optimal protection limits were proposed.

Most existing studies focus on medical service capacity allocation and scheduling from the perspective of service provider side except for [1,15,16]. Ref. [1] proposed contracted based MRI reservation process, and determined CTS decisions and RTS assignment policy by combining stochastic programming model and average-cost MDP. It differs from the previous studies on critical resource scheduling by investigating the problem from a totally different perspective and explores solutions from the perspective of a given class of customers, i.e., stroke patients. CTS are pre-reserved for stroke patients by taking their average waiting time and unused CTS into account. On this basis, [15,16] considered the possibility of canceling some CTS and proposed average-cost MDP approaches. Ref. [15] determined simultaneously RTS assignment policy and one-day advance cancelation policy for CTS; whereas [16] determined the RTS assignment policy, one-day and two-day advance cancelation policy for CTS. This paper investigates different strategies for implementing an MRI-contract in order to reduce waiting time variation. Advance cancelation of CTS is not considered in this paper.

3. Problem and strategies

3.1. MRI time slot contracting and reservation

In order to reduce the waiting times of stroke patients, we proposed in [1] a contract-based MRI examination reservation process. In this reservation process, NVD treating stroke patients is allocated a certain number of time slots every day which is called Contracted Time Slots (CTS). The distribution of CTS over time will be called the **contract**. When the queue for CTS is too long, stroke patients can also use additional time slots via regular reservation which is called Regular Time Slots (RTS). Patients either wait for MRI time slots in a CTS queue or are directed to RTS via lengthy regular reservation process (30–40 days). This strategy will be called **RTS assignment policy**. Although the combination of contract and RTS assignment policy greatly reduces the average waiting time of stroke patients, the variation of patients' waiting time is quite large. The "unlucky" patients assigned to RTS have to wait much longer than those waiting for CTS.

In order to improve waiting time distribution, this paper proposes three new implementation strategies. These new strategies still make use of the same contract. With these new strategies, no patient is directed to wait for RTS reservation, and all patients wait in the same queue for MRI time slots. Additional MRI time slots are reserved by NVD through the regular reservation process. The reservation depends on the queue length of patients, and the corresponding time slots will be available in T time periods later. These additional time slots and CTS are pooled together and given to strokes patients on a FIFO basis. These new reservation processes are called **RTS reservation policies**.