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Patient and Resource Scheduling of Multi-Step Medical Procedures in Nuclear Medicine

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Abstract The rise in demand for specialized medical services in the U.S has been recognized as one of the contributors to increased health care costs. Nuclear medicine is a specialized service that uses relatively new technologies and radiopharmaceuticals with a short half-life (minutes) for diagnosis and treatment of patients. Nuclear medicine procedures are multi-step and have to be performed under restrictive time constraints. Consequently, managing patients in nuclear medicine clinics is a very challenging problem with very little research attention. In this paper, we derive algorithms for scheduling nuclear medicine patients and resources. We validate our algorithms using simulation of an actual nuclear medicine setting and historical data. We consider performance measures of both the patient's and the nuclear medicine manager's interests. The results we obtain provide useful insights into managing patients and resources in nuclear medicine clinics and can be applicable to many other similar health care settings.

Keywords Health care · nuclear medicine · patient service · scheduling

1 Introduction

Nuclear medicine is a sub-specialty of radiology that provides highly specialized services by means of new technology for diagnosis and treatment of patients. There has been a rise in demand for such specialized services in the U.S. and this has been attributed as a contributor to the increased health care costs, which surpassed those in other nations that provide similar services. Physicians are becoming more prone to asking patients to undergo specialized procedures in order to obtain more accurate diagnoses. However, scheduling patients and resources in specialized clinics such as nuclear medicine remains a challenging problem. This may be attributed to the increased demand in services and the nature of nuclear medicine procedures. In this paper, we derive algorithms to assist nuclear medicine managers towards scheduling nuclear medicine patients and resources more efficiently. We consider both the patient's and the manager's perspectives.

Nuclear medicine procedures (tests or studies) are typically multi-step, involve multiple resources, and require the administration of a radiopharmaceutical (radioactive isotope, e.g., iodine-131) to the patient. This allows for images of specific body organs to be taken (scan) using gamma cameras that sense the radiation emitted by the radiopharmaceutical. Since radiopharmaceuticals have a short half-life (minutes), their decay imposes strict time constraints on scheduling patients and resources in order to get good quality scans. Thus scheduling patients in nuclear medicine requires very strict procedure protocols, which if not followed can result in poor scans. In this case, time, money and resources are wasted, and the patient has to be rescheduled for another day after having been exposed to radiation. Some nuclear medicine tests require only a single scan while others involve multiple scans in a day or multiple days. Each scan takes several minutes to hours to complete.

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Nuclear medicine procedures require the utilization of the several resources such as a technologist, gamma camera, radiopharmaceutical, and sometimes, a nurse or EKG technician. The gamma cameras may cost up to a million dollars and thus have to be used and managed effectively. Since at many nuclear medicine clinics radiopharmaceuticals are prepared at remote radiopharmacies from the clinic, scheduling of their delivery, patient injection and image acquisition requires lead time and must be carefully managed. Radiopharmaceuticals may cost up to several hundreds of dollars. The resources needed to perform each procedure step must be available at the scheduled times. A patient has to be rescheduled if the procedure is not completed successfully. Therefore, scheduling patients, resources, and radiopharmaceutical preparation and delivery is a very challenging problem for nuclear medicine departments. Consequently, providing a high quality of service to the patient through the use of mathematical techniques is of great interest to nuclear medicine managers. However, the characteristics found in the management of patients and resources in nuclear medicine makes it a unique problem with limited research reported in the literature. Furthermore, very few commercial packages are available for patient service management and the available few lack algorithms for scheduling patients and resources efficiently.

Several practical issues have to be considered to achieve a well designed system for patient service management in nuclear medicine. For example, scheduling decisions must satisfy the goals of both patients and managers. In this work, we consider both perspectives. Both points of view are important when designing scheduling policies to improve the service offered to patients and the way resources are utilized. The contributions of this paper include mathematical algorithms for scheduling patients and resources in nuclear medicine that consider both patient and manager perspectives. These scheduling algorithms are implemented and tested using the discrete event simulation model proposed by Pérez et al. [12]. We obtain computational results that provide useful insights into managing patient service and resources in nuclear medicine. While this paper focuses on nuclear medicine, we believe that results can be applied to many other similar health care settings that may not be as complex as nuclear medicine. For example, our results can be applied to diagnostic imaging areas such as magnetic resonance imaging (MRI) and computed axial tomography (CT Scan).

The rest of the paper is organized as follows: In Section 2 we review closely related work and provide preliminaries on nuclear medicine resources and procedures in Section 3. We derive algorithms for scheduling nuclear medicine patients and resources in Section 4. We report on a computational study to quantify important trade-offs among different patient and resource scheduling strategies in Section 5. We also discuss the results and highlight the insights into the complexity of nuclear medicine patient service management. We end the paper with some concluding remarks and directions for further research in Section 6.

2 Literature Review

Facilities dedicated to the diagnosis and treatments of diseases are vital in comprehensive health care systems. Mettler et al. [9] found a 5-to-6 fold increment medical diagnostic procedures requests whereas the U.S. population increased by approximately 50%. This increment in demand has been identified as one of the causes for increased health care costs in the U.S. [18]. Facilities that are hospital-based such as radiology clinics are highly specialized and characterized for providing different types of services to patients. Equipment utilized for diagnosis procedures are usually very expensive and the unique characteristics of these procedures make finding an efficient way of scheduling patients and resources a complex and dynamic tasks [17]. A necessary condition for overall hospital efficiency is the effective utilization of medical diagnosis facilities such as nuclear medicine because they are used by almost every patient that enters a hospital [10].

Prior research on patient service management in nuclear medicine is very limited. Operations research techniques such as simulation and mathematical optimization have been considered as viable approaches for patient and resource scheduling in radiology clinics. Most of the work existing in the literature seems to concentrate in patient scheduling for outpatient clinics [3,8] and does not take into account the complexities of nuclear medicine. In fact, Gupta and Denton [7] identified the problem of scheduling patients in highly constrained health care environments as a current research open challenge. We refer readers to recent outpatient appointment scheduling research surveys by Cayirli and Veral [2] and Gupta and Denton [7].

Mathematical optimization has been applied to the problem of scheduling outpatients in specialty medical clinics. Conforti et al. [4] proposed an optimization model for outpatient scheduling within a radiotherapy department where patients have to visit the treatment center several times during the week. Green et al. [6] studied the problem of scheduling different types of patients that arrive randomly during the week to a MRI facility. They present a finite-horizon dynamic program for an appointment schedule that allows at most one

Table 1 Human resources responsibilities in nuclear medicine

Technologist	Nurse	Physician	Manager
IV access	IV access	IV access	IV access
Radiopharmaceutical administration	Radiopharmaceutical administration	Radiopharmaceutical administration	Radiopharmaceutical administration
Draw doses	Draw doses	Draw doses	Draw doses
Radiopharmaceutical preparation			Radiopharmaceutical preparation

patient per time period and a single server. The problem of managing patients in a CT scan clinic is addressed by Patrick and Puterman [11]. They present a mathematical formulation of the problem that returns a patients' reservations to maximize the utilization of resources subject to an overtime constraint. The authors assume a pool of patients that can be allocated to the system when time slots become available. The authors used simulation to show a decrease in patients waiting time for service. Vermeulen et al. [17] devise and adaptive approach for automatic optimization of resource schedules in a CT scan facility. They use simulation for case analysis and demonstrate that their approach makes an efficient use of the resource capacity available.

Patient service satisfaction in outpatient clinics is difficult to measure because it mostly depends on patients perspectives. The most common performance measures that are used to quantify patients perceptions about the service received in outpatient clinics include two types of patient *waiting times*. The first one is waiting time *Type 1*, which is the patient waiting time from the moment service is requested to the actual appointment [16]. The second is waiting time *Type 2*, which is the time the patient waits from the arrival to the clinic until service is started [1,3,5,16]. The other performance measures are the percentage of time patient requests for an appointment are satisfied [6], and the time the patient spends inside the system [13,15].

Patient service satisfaction is important but in order to design good appointment systems health care managers interests also have to be taken into account. Health care managers are more concerned with the quality of service provided and the *profitability* of the business. Performance measures related to the profitability of the business include limiting human resources overtime [1,5], increasing resource utilization [3,5,16] and patient throughput [14]. These performance measures are commonly used in the literature to describe management perspectives and they have to be used in tandem with those corresponding to the patient perspective to achieve a 'good' appointment system.

3 Overview of Nuclear Medicine Clinics Operation

A typical nuclear medicine department involves several interacting entities. These include humans (staff), procedures/tests, stations, and patients. We describe these entities in the context of their interaction with the appointment scheduling system, and then summarize the performance measures used in nuclear medicine.

3.1 Nuclear Medicine Entities

Human Resources. We have four types of human resources: technologists, nurses, physicians, and managers. Each human resource possesses his/her own expertise and experience, which determine the set of activities they can perform and the amount of time required to complete each activity. Human resources that have more experience are expected to complete their tasks relatively quickly. Some of the activities that can be performed by the members of the staff are listed in Table 1.

Procedures (Tests). Procedures/tests are usually requested by the patient's primary physician or attending physician. So unlike general outpatient clinics, patient *no shows* is not an issue in nuclear medicine since patients show up for their appointments most of the time. The nuclear medicine procedures provide physicians with information about the function of organs of the human body for diagnosis purposes but they are also used for patient treatment. An example list of nuclear medicine procedures with their current procedural terminology (CPT) is presented in Table 2.

Each procedure requires the administration of a radiopharmaceutical and the number of steps for each procedure range from 3 to 11. Each step duration varies depending on the human resource in charge but it has to be completed within the time window established by the procedure protocol. As an example the *MSC-bone imaging* procedure is described in Table 3. This

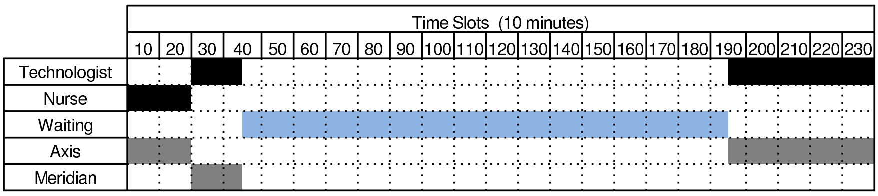

Fig. 1 Schedule for procedure 78315: MSC-bone imaging (three phase)

Table 2 Examples of nuclear medicine procedures.

CPT Code	Name
78465	Cardiovascular Event (CVE) Myocardial Imaging (SP-M)
78815	Positron Emission Tomography (PET)/ Computed Tomography (CT) skull to thigh
78306	MSB-bone imaging (whole body)
78315	MSC-bone imaging (three phase)
78223	GIC-Hepatobiliary imaging
78472	CVJ-cardiac blood pool
78585	REB-Pulm perfusion / ventilation
78006	ENC-Thyroid imaging
78195	HEE-Lymphatic imaging
78464	CVD-Myocardial imaging (SP-R ORS)

Table 3 Procedure 78315: MSC-bone imaging (three phase)

Step	Activity	Time (mins.)	Station	Human Resource
1	Radioph. injection	20	Axis; Meridian; P2000	Technologists; Nurse; Manager
2	Imaging	15	Axis; Meridian; P2000	Technologists; Manager
3	Patient Wait	150-180	Waiting	
4	Imaging	45	Axis; Meridian; P3000	Technologists; Manager

procedure takes a minimum of 230 minutes for completion and requires the involvement of several human resources. Figure 1 shows a representation of the schedule generated to take care of a patient requesting the *MSC-bone imaging* procedure.

Table 4 Performance measures for patient satisfaction in health care.

Name	Description	Refs.
Waiting time type 1	Time patient wait from the time of calling for an appointment until the date of the appointment	[16]
Preference ratio	Percentage of times patient requests for an appointment are satisfied	[6]
Cycle time	Time patient spends in the system	[13], [15]

Stations and Equipment. Nuclear medicine departments are subdivided into stations where procedures/tests are performed. Each station contains at least one type of equipment. Stations are classified depending on the equipment they contain. Nuclear medicine equipment includes different types of gamma cameras and treadmills for cardiovascular tests. All the entities needed to perform a procedure step have to be present in the station before starting any activity. For example, in order to perform a scan the technologist and the patient have to be present in the station and the camera has to be configured to take the appropriate image. The time spent by these entities in the stations will depend on several things that include the expertise of the human resource and the procedure protocol.

Patients. Requests for procedures are managed by a call center. A receptionist takes care of these requests by finding an appointment in the system for the patient. Requests are always for a single procedure and sometimes patients will have a preference for the appointment date. The schedule provided to the patient is determined by the scheduling policies or algorithms used by the clinic.

3.2 Performance measures

We use performance measures that take into account both patient and manager perspectives to evaluate how patients and resources are managed. These are described in Tables 4 and 5.

Table 5 Managers performance measures.

Name	Description	Refs.
Equipment utilization	Maximize utilization	[16], [5]
Human resource utilization	Most adequate number of human resources while maximizing utilization	[5], [3]
Patient throughput	Number of patients served per day	[14]

4 Patient and Resource Scheduling

We now turn to patient and resource scheduling in nuclear medicine. In particular, we derive four algorithms for scheduling nuclear medicine patients and resources: *As-Soon-As-Possible* (ASAP), *Patient Preference* (PP), *Combination* (COMB), and *Fixed Resource* (FR) algorithms. The ASAP algorithm schedules patients as soon as possible based on the availability of the resources, while the PP algorithm schedules patients and resources based on the patient preferred appointment day of the week. The COMB algorithm schedules patients and resources based on the patient's preferred day of the week for the appointment. However, if the patient's preference results in a wait of more than one month, an earlier appointment is considered using the ASAP algorithm. The FR algorithm schedules patients by fixing specific technologists to specific stations and is based on the real-life practical experience of the last two authors.

To mathematically describe the algorithms we use the notation given in Table 6.

We require that the sets $X_r = \{(d,t) |\ \underline{h} \leq d \leq \overline{h},\ 1 \leq t \leq \tau\}$ and $Y_s = \{(d,t) |\ \underline{h} \leq d \leq \overline{h},\ 1 \leq t \leq \tau\}$. The sets X_r and Y_s include all the time slots that are already scheduled. Similarly, the set $A_j = \{(d,t) |\ \underline{h} \leq d \leq \overline{h},\ 1 \leq t \leq \tau\}$.

For ease of exposition, we first briefly describe the methods (functions) that we use in the algorithms, and then state the algorithms.

- *getRadiopInfo*(p_j): returns w.
- *getNumberSteps*(p_j): returns k_p.
- *getStartingDay*(d, q): returns the earliest day the patient can be scheduled d^*.
- *getTimeSlots*$(p_j, \hat{k})$: returns n.
- *getHumanResource*(p_j): returns R_p.
- *getStation*(p_j): returns S_p.
- *getResourceSchedule*(r): returns X_r. The method is also used to get Y_s.

We define the *CheckSchedule*() method to check the schedule availability of either a human resource or a station during a given time interval. A detailed description of this method is provided using the following pseudocode. We use the left arrow ($\leftarrow$) to denote assignment.

$CheckSchedule(d, t, r, n)$

```
1  $X_r \leftarrow getResourceSchedule(r)$;
2  for $t \leq t + n$;
3      if $(d, t) \in X_r$;
4          return $false$;
5      else $t \leftarrow t + 1$;
6  return $true$;
```

The pseudocode illustrates the case for checking the schedule of a human resource r. The schedule is requested on the first line of the pseudocode. The objective is to verify the availability of this resource during the time period starting at time t to time $t + n$. If any of the time slots that form part of this time period are included in the set X_r, a $false$ value is returned. On the other hand, if none of the time slots is found in the set X_r a $true$ value is returned indicating that the resource is available. The $CheckSchedule()$ method is invoked by another method named $Search$, which is describe below. The $Search$ method verifies that a qualified combination of resources (human resource and station) is available to perform the requested procedure step during the time period under consideration. The boolean variable $\alpha_r = true$ if a human resource is available, otherwise $\alpha_r = false$. Similarly $\alpha_s = true$ if a station is available, otherwise $\alpha_r = false$. The following pseudocode lists the steps of the $Search$ method.

$Search(d, t, R_p, S_p, n)$

```
1  while $R_p \neq \emptyset$;
2      $\alpha_r \leftarrow CheckSchedule(d, t, r, n)$, where $r \in R_p$;
3      if $\alpha_r == true$;
4          while $S_p \neq \emptyset$;
5              $\alpha_s \leftarrow CheckSchedule(d, t, s, n)$, where $s \in S_p$;
6              if $\alpha_s == true$;
7                  return $true$;
8              else $S_p \backslash s$;
9          return $false$;
10     else $R_p \backslash r$;
11 return $false$;
```

The *Search*() method uses a breath-first search to select a human resource from the R_p set as well as to select a station from the S_p set. Initially the method picks a human resource from the R_p set and calls the method *CheckSchedule*() to verify the resource's availability (lines 1 and 2). If α_r is $false$ the selected human resource is not available and is removed from the set (line 10). Otherwise, if α_r is $true$ a station is selected from the set S_p and the method *CheckSchedule*() is called to verify the station's availability (lines

Table 6 Scheduling algorithms sets and parameters.

	Sets
J:	Set of patients, indexed j.
S:	Set of stations, indexed s.
R:	Set of human resources, indexed r.
P:	Set of nuclear medicine procedures, indexed p.
R_p:	Set of human resources qualified to perform procedure p.
S_p:	Set of stations where procedure p can be performed.
A_j:	Set of day and time slot pairs, (d,t), for patient j.
X_r:	Set of day and time slot pairs, (d,t), for human resource r schedule.
Y_s:	Set of day and time slot pairs, (d,t), for station s schedule.
Q:	Set of days of the week, indexed q.
	Parameters
(d_j,t_j):	Call day and time for patient j.
p_j:	Nuclear medicine procedure for patient j.
k_p:	Total number of steps for procedure p, indexed $\hat{k}=1,\cdots,k_p$.
τ:	Total number of time slots in a day, indexed $t=1,\cdots,\tau$.
n:	Number of time slots required for procedure p.
w:	Number of days before arrival of radiopharmaceutical after placing order.
$h=[\underline{h},\overline{h}]$:	Scheduling horizon in days, with $\underline{h}$ being the initial day and $\overline{h}$ being the last day.

3 to 5). If α_s is $false$ the selected station is not available and is removed from the set (line 8). Otherwise, if α_s is $true$ the method returns $true$ indicating that a combination of human resource and station is available during the requested time period (line 7). The notation and description of the methods provided allow us now to state the scheduling algorithms.

The patient and resource scheduling algorithms we propose share the same overall structure. This is captured in the next pseudocode, *Scheduling Algorithm*. The algorithms differ in the way they implement the method *ServeRequest-Algorithm*(). In all the algorithms we assume that no more that one patient can be scheduled on the same resource at the same time, and that the scheduling horizon is long enough so that no patient request will be dropped. All our algorithms take the following major steps:

Scheduling Algorithm(A)

```
1 $J \leftarrow \emptyset$
2 while $d \leq \overline{h}$
3     while $t \leq \tau$
4         do $J \cup \{p_j\},\ d_j \leftarrow d,\ t_j \leftarrow t$;
5         $A_j \leftarrow$ ServeRequest-Algorithm$(d_j, t_j, p_j)$;
```

Initially, patient set J is empty (line 1). The algorithm's scheduling horizon is defined in lines 2 and 3. Requests for service are handled on line 4 by adding the procedure request to set J and by assigning the call day and time to d_j and t_j, respectively. On line 5 the *ServeRequest-Algorithm*() is invoked to find an appointment for the patient. The *ServeRequest-Algorithm*() method depends on the type of scheduling algorithm used.

The ASAP algorithm is invoked by a method *ServeRequest-ASAP*(). This algorithm schedules patients in the first spot available in the scheduling horizon. The earliest the appointment can be scheduled is determined by the radiopharmaceutical arrival time. If no radiopharmaceutical is needed for the procedure, the earliest appointment is the day after the patient's call. If a radiopharmaceutical is needed, the appointment starting point is the earliest day and time the radiopharmaceutical can arrive at the clinic. The steps for the ASAP algorithm are given below. The boolean variable α is used to report the availability of both human resource and station.

ServeRequest-ASAP(d_j, t_j, p_j)

```
1  $A \leftarrow \emptyset$;
2  $w \leftarrow$getRadiopInfo $(p_j)$;
3  $d \leftarrow d_j + w,\quad t \leftarrow 0,\quad \hat{k} \leftarrow 1$;
4  $k_{p_j} \leftarrow$ getNumberSteps $(p_j)$;
5  while $\hat{k} \leq k_{p_j}$;
6      $n \leftarrow$ getTimeSlots$(p_j, \hat{k})$;
7      $R_p \leftarrow$ getHumanResource$(p_j)$;
8      $S_p \leftarrow$ getStation$(p_j)$;
9      while $d \leq \overline{h}$;
10         while $t \leq \tau$;
11             $\alpha \leftarrow$ Search$(d, t, R_p, S_p, n)$;
12             if $\alpha == false$ ;
13                 $t \leftarrow t + 1$;
14             else $A \cup \{(d,t)\},\quad \hat{k} = \hat{k} + 1$;
15         $d = d + 1$;
16 return $A$;
```

Line 1 initializes the appointment set A which will contain the times reserved for patient j appointment. The algorithm then finds the number of days (w) needed for the radiopharmaceutical to get to the clinic, and the number of steps (k_{p_j}) for procedure (p_j) by using the methods *getRadiopInfo*() and *getNumberSteps*(), respectively (lines 2-4). For each procedure step we need to find the number of time slots needed for the task, the human resources that can perform the task, and the stations that can be used to perform the task (lines 5-8). The earliest the appointment can be scheduled depends on w. If no radiopharmaceutical is needed, w is set to 1, which means that the search will start the day after the call is received (line 9). Line 10 keeps track of time slots. The *Search*() method is invoked in line 11. If α is $false$, no resources are available during the time period requested and t is incremented by 1, allowing to search for the availability of the next time period (lines 12-13). Otherwise, if α is $true$, the algorithm proceeds to the next step (line 14). After completing all steps the algorithm returns the appointment set A.

The PP algorithm and is invoked by using the method *ServeRequest-PP*(). Unlike the ASAP algorithm, the PP algorithm takes into account the patient perspective and allows the patient to provide preferred day(s) of the week for the appointment (q). Again, the earliest time an appointment can be scheduled is determined by w, if a radiopharmaceutical is needed. The PP algorithm can be stated as follows:

ServeRequest-PP(d_j, t_j, p_j, q)

```
 1 $A \leftarrow \emptyset$;
 2 $w \leftarrow$getRadiopInfo $(p_j)$;
 3 $d \leftarrow d_j + w$,   $t \leftarrow 0$,   $\hat{k} \leftarrow 1$;
 4 $k_{p_j} \leftarrow$ getNumberSteps $(p_j)$;
 5 while $\hat{k} \leq k_{p_j}$;
 6       $n \leftarrow$ getTimeSlots$(p_j, \hat{k})$;
 7       $R_p \leftarrow$ getHumanResource$(p_j)$;
 8       $S_p \leftarrow$ getStation$(p_j)$;
 9       $d^* \leftarrow$ getStartingDay$(d, q)$;
10       while $d^* \leq \overline{h}$;
11             while $t \leq \tau$;
12                   $\alpha \leftarrow Search(d^*, t, R_p, S_p, n)$;
13                   if $\alpha == false$ ;
14                         $t \leftarrow t + 1$;
15                   else $A \cup \{(d^*, t)\}$,   $\hat{k} \leftarrow \hat{k} + 1$;
16             $d^* \leftarrow d^* + 5$;
17 return $A$;
```

Observe that the PP algorithm is very similar to the ASAP algorithm. The main difference is in how the PP algorithm selects the earliest day to begin the search for an appointment in the schedule. In line 9 a function called *getStartingDay*() compares the day requested by the patient and the earliest day the radiopharmaceutical can get to the clinic, and returns the earliest day the appointment can be scheduled (d^*). If an appointment cannot be scheduled on that day, the algorithm checks next week (line 16) until a space in the schedule satisfying the patient request is found.

The COMB algorithm combines ASAP and PP algorithms. The first goal of the COMB algorithm is to find an appointment when the patient preference is satisfied. If the waiting time for the appointment is longer than a month, the ASAP algorithm is invoked to search for an alternative appointment in which the patient does not have to wait that long. The boolean variable α is used to report the availability of both human resource and station, where $\alpha = true$ means that both resources are available. A second boolean variable, β, assumes a $true$ value when the amount of time the patient has to wait for the appointment is less than a month. The method *getAppointWait*() is used to determine the amount of time the patient will have to wait for an appointment when his preference is taken into consideration. The COMB algorithm can be stated as follows:

ServeRequest-COMB(d_j, t_j, p_j, q)

```
 1 $A \leftarrow \emptyset$;
 2 $w \leftarrow$getRadiopInfo $(p_j)$;
 3 $d \leftarrow d_j + w$,   $t \leftarrow 0$,   $\hat{k} \leftarrow 1$;
 4 $k_{p_j} \leftarrow$ getNumberSteps $(p_j)$;
 5 while $\hat{k} \leq k_{p_j}$;
 6       $n \leftarrow$ getTimeSlots$(p_j, \hat{k})$;
 7       $R_p \leftarrow$ getHumanResource$(p_j)$;
 8       $S_p \leftarrow$ getStation$(p_j)$;
 9       $d^* \leftarrow$ getStartDay$(d, q)$;
10       while $d^* \leq \overline{h}$;
11             while $t \leq \tau$;
12                   $\alpha \leftarrow Search(d^*, t, R_p, S_p, n)$;
13                   if $\alpha == false$ ;
14                         $t \leftarrow t + 1$;
15                   else if $\alpha == true$  &&  $\hat{k} == 1$ ;
16                         $\beta \leftarrow getAppointWait(d_j, t_j, d^*, t)$;
17                               if $\beta == true$;
18                                     $A \cup \{(d^*, t)\}$,   $\hat{k} \leftarrow \hat{k} + 1$
19                               else ServeRequest-ASAP$(d_j, t_j, p_j)$;
20                   else $A \cup \{(d^*, t)\}$,   $\hat{k} \leftarrow \hat{k} + 1$;
21             $d^* \leftarrow d^* + 5$;
22 return $A$;
```

The COMB algorithm follows the PP algorithm steps until line 12. At this point the algorithm verifies the value of α in order to proceed. If α is $false$ it means that a combination of human resource and station was not found available during the time period requested. The algorithm then proceeds to increment the time period by one, allowing to search for the availability of the next time period (line 14). Otherwise, if α is $true$, the algorithm proceeds to line 16 to check whether or not the time between the patient call and the initial time of the appointment is less than a month (line 16). If so, β is $true$ and the time period found is included in the patient schedule (lines 17-18). However, if β is $false$ the algorithm ASAP algorithm is invoked (line 19) and the patient is scheduled on the first available spot in the schedule. The rest of the algorithm proceeds as the PP algorithm.

The FR algorithm is a variation of the COMB algorithm and has been used in a practical setting. This algorithm first tries to satisfy the patient preferences; but, if the waiting time for the appointment is longer than a month, the ASAP algorithm is invoked to search for an alternative earlier appointment. The difference between the COMB and FR algorithms is in the way the human resources are assigned to patients. In the FR algorithm a group of human resources (e.g. 2 technologists) are assigned to always serve patients in specific stations. For example, technologist *1* has to serve all patients whose procedures require the use station x while technologist *2* has to serve all patients whose procedures require the use of station y. We use $\tilde{r}$ and $\tilde{s}$ to denote the human resource and station, respectively, that have been fixed. To describe the FR algorithm we need to modify the *Search*() method described earlier as follows:

Search(d, t, R_p, S_p, n)

```
1  while $R_p \neq \emptyset$;
2      $\alpha_r \leftarrow CheckSchedule(d, t, r, n)$, where $r \in R_p$;
3      if ($\alpha_r == true$ && $r == \hat{r}$);
4          return $true$;
5      else if ($\alpha_r == true$ && $r \neq \hat{r}$);
6          while $S_p \neq \emptyset$;
7              $\alpha_s \leftarrow CheckSchedule(d, t, s, n)$, where $s \in S_p$;
8              if $\alpha_s == true$;
9                  return $true$;
10             else $S_p \backslash s$;
11         return $false$;
12     else $R_p \backslash r$;
13 return $false$;
```

The *Search*() method uses a breath-first search to select a human resource from the set R_p as well as to select a station from the set S_p. The method first picks a human resource from R_p and calls the method *CheckSchedule*() to verify the resource's availability (lines 1 and 2). If α_r is $false$ the selected human resource is not available and is removed from the set (line 14). Otherwise, if α_r is $true$ and the human resource selected is ($\hat{r}$), the method returns *true*. In this case there is no need to check the station schedule since the human resource is fixed to a station. On the other hand, if α_r is $true$ and the human resource is not fixed, a station is selected from the set S_p and the method *CheckSchedule*() called to verify its availability (lines 5 to 7). If α_s is $false$, the selected station is not available and is removed from the set (line 8). Otherwise, if α_s is $true$ the method returns $true$, which means that a human resource and a station is available during the requested time period (line 9). The FR algorithm can be summarized as follows:

ServeRequest-FR(d_j, t_j, p_j, q)

```
$A \leftarrow \emptyset$;
$w \leftarrow getRadiopInfo\ (p_j)$;
$d \leftarrow d_j + w$,   $t \leftarrow 0$,   $\hat{k} \leftarrow 1$;
$k_{p_j} \leftarrow getNumberSteps\ (p_j)$;
while $\hat{k} \leq k_{p_j}$;
    $n \leftarrow getTimeSlots(p_j, \hat{k})$;
    $R_p \leftarrow getHumanResource(p_j)$;
    $S_p \leftarrow getStation(p_j)$;
    $d^* \leftarrow getStartDay(d, q)$;
    while $d^* \leq \overline{h}$;
        while $t \leq \tau$;
            $\alpha \leftarrow Search(d^*, t, R_p, S_p, n)$;
            if $\alpha == false$ ;
                $t \leftarrow t + 1$;
            else if $\alpha == true$ && $\hat{k} == 1$ ;
                $\beta \leftarrow getAppointWait(d_j, t_j, d^*, t)$;
                if $\beta == true$;
                    $A \cup \{(d^*, t)\}$,   $\hat{k} \leftarrow \hat{k} + 1$
                else $ServeRequest\text{-}ASAP(d_j, t_j, p_j)$;
            else $A \cup \{(d^*, t)\}$,   $\hat{k} \leftarrow \hat{k} + 1$;
        $d^* \leftarrow d^* + 5$;
return $A$;
```

5 Application

To test and validate our algorithms we applied them to an actual nuclear medicine setting. We first describe the configuration of the nuclear medicine setting and then present the computational results.

5.1 Nuclear Medicine Setting

The scheduling algorithms we propose were applied to the Scott and White Health System Nuclear Medicine Department in Temple, Texas. This facility is one of the largest fully-accredited nuclear laboratories for general nuclear imaging and non-imaging, nuclear cardiology and positron emission tomography (PET) scan in the country. The Scott and White Clinic operates nine hours a day, five days a week and is not open on weekends. The staff consists of sixteen members. Every member of the group performs tasks according to their expertise and years of experience. There are eight technologists and two EKG technologists in this clinic. The technologists have several responsibilities that include drawing doses and image acquisition. EKG technologists perform stress exams for cardiac tests. A nurse is in charge of helping to draw doses. In the absence of one of the staff members, the division manager can perform that staff member's tasks (see Table 1). The remaining staff members include two fulltime nuclear medicine physicians, two radiology residents, and a staff cardiologist.

The clinic contains different types of gamma cameras. There are seven gamma cameras. Five of these cameras are of planar configuration, capable of performing 2D whole-body imaging and 3D Single Photon Emission Computed Tomography (SPECT). One of the other two gamma cameras is used for a small field of view and the other one is for imaging only. There are three stress rooms in the cardiac area and two of them have treadmills. The room with no treadmill is used for chemical stress testing for patients who cannot walk on a treadmill. The PET facility has one imaging camera, three patient preparation rooms and one receiving area for radiopharmaceutical delivery. Sixty different procedures are performed in the Scott and White Clinic. Table 2 of Section 3 shows the procedures performed more frequently at the clinic for a year of observation.

Preliminary experiments were conducted to gain management insights into the impact of the scheduling approaches on patient service. The performance measures listed in Section 3 were used to quantify service levels based on both patient and management perspectives. In our computational study, we used historical information regarding patients who were served at the facility during a particular year. We only considered the nuclear medicine procedures listed in Table 2. Since in the PP algorithm we need to specify the patient's preferred day for the appointment, we used the uniform distribution to decided which day of the week (Monday through Friday) was the patient's preference. The uniform distribution was based on the historical data for the nuclear medicine facility.

5.2 Computation Results

We performed computational experiments using the scheduling algorithms presented in Section 4 and historical data. These algorithms were implemented within the simulation model proposed by [12]. One experiment was conducted for each scheduling algorithm. Experiments consisted of 20 replications and using a one-year replication length with a three months warm-up period. Each experiment was performed using the same nuclear medicine department configuration. All the computational experiments were executed on a DELL Optiplex GX620 with a Pentium D processor running at 3.0GHz with 3.5GB RAM.

The experimental results are reported using tables and figures. Table 7 shows the CPU time and patient throughput (mean and standard deviation) for each experiment. The average simulation times obtained for each experiment were relatively low, which is a desirable property when quick decisions have to be made. The number of patients served determine the revenue of the nuclear medicine department. Results show that average highest number of patients served in the clinic is achieved under the ASAP algorithm, followed by the COMB and FR algorithms. The ASAP algorithm is able to accommodate more patients in the system because it is not constrained by patients or managerial preferences. PP algorithm showed the lowest average number of patients served during the year. This algorithm is always forced to satisfy the preferred day requested by the patient, which constrains the scheduling options and the possibilities of accommodating more patients. All the results under the FR algorithm, which imitates the way patients are scheduled in the real setting, are within 15% of the actual results for that year, thus validating our results.

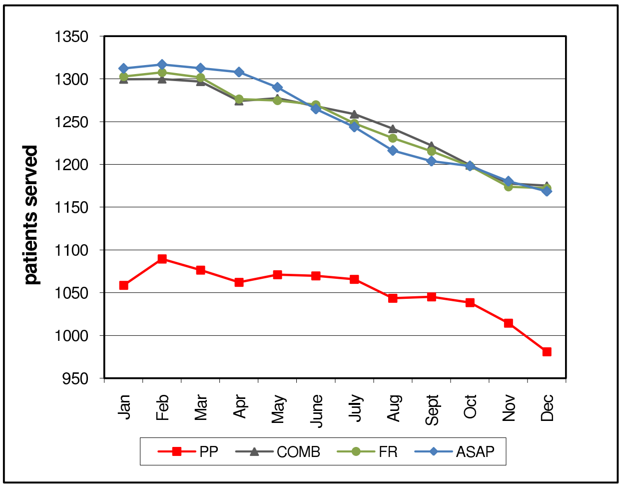

Fig. 2 Number of patients served per month

Figure 2 shows the average number of patients served per month for each experiment. The graph shows a decreasing trend for the average throughput per month corresponding to a decrease in demand during the year based on the clinic's historical records. An interesting observation to make is that the results show that none of the top three algorithms performs the best every month. For example, the ASAP algorithm provides the higher throughput in the first six months, probably due to higher demand coupled with open scheduling time slots at the beginning of the year. The COMB and FR algorithm perform relatively well from June through the end of the year. PP algorithm performs the worst over the whole year. The results indicate that none of the top three performers dominate in terms of patient throughput due to the tradeoffs among different competing factors in scheduling the patients and resources.

Utilization of nuclear medicine equipment under each scheduling algorithm is reported in Table 8 while the numbers are plotted in Figure 3. The graph shows that for ASAP, COMB and FR algorithms, the utilization of most of the equipment is almost the same and is over

Table 7 Simulation time, patients served and system throughput

	ASAP		PP		COMB		FR	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
CPU Time (secs)	812.65	22.23	932.12	60.70	872.16	11.05	809.23	10.09
Patients Served	15015.35	72.11	12616.90	96.84	14991.53	63.97	14972.67	64.51
patients/day	62.56	0.30	52.57	0.40	62.46	0.27	62.39	0.27

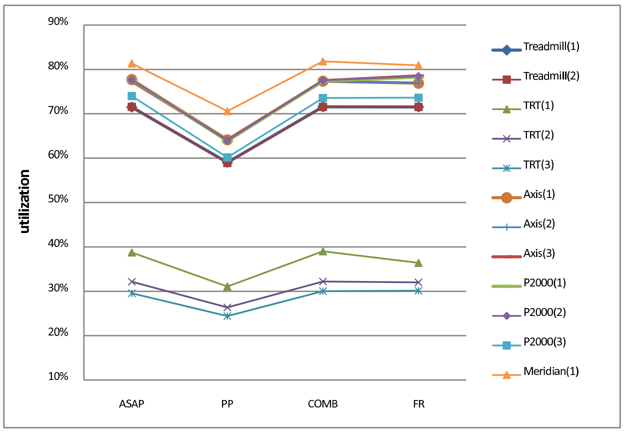

Fig. 3 Equipment percent (%) utilization

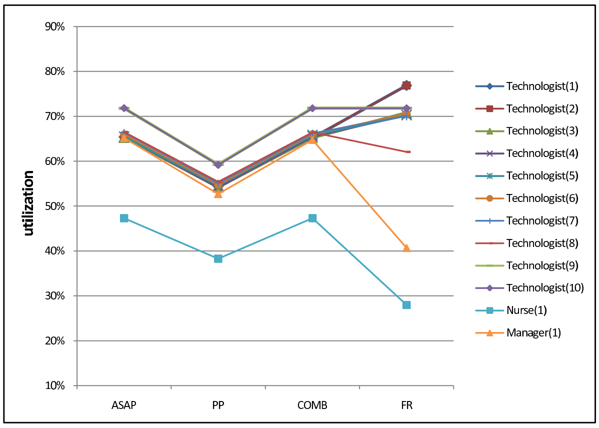

Fig. 4 Human resource percent (%) utilization

70%. Equipment utilization under PP is always lower. This may be explained by the fact that fewer patients are served under this scheduling algorithm.

Utilization of the staff is reported in Table 9 and the results are plotted in Figure 4. Human resource utilization under ASAP and COMB is very similar and is higher than the utilization achieved under the PP algorithm. A load balance routine was included in the ASAP, PP, and COMB algorithms to evenly assign human resources to patients. However in the FR algorithm the manager decides the human resources that will be fixed to specific stations and the balancing of assignments is only done for those resources that are not fixed. Consequently, under the FR algorithm utilization for Technologists 1 and 2 is higher. These two human resources are fixed to specific stations where most of the procedures are scheduled. Also, notice that, on the contrary, the utilization of Nurse, Manager and Technologist 8 are reduced. The workload of these three staff members is absorbed by Technologist 1 and 2.

Table 10 shows the results obtained for the average number of days a patient has to wait from the day the procedure is requested, to the day the appointment is given. As expected, patients wait less under ASAP with a waiting time of about two days. The PP algorithm reported the largest waiting time, which is almost three weeks. COMB and FR reported similar waiting times, with the FR giving only sightly less.

Finally, Table 11 shows the results obtained for the preferences ratio (Section 3), which is the percentage of time a patient request for an appointment is satisfied. PP reports the highest preference ratio of 100%, while both COMB and FR resulted in around 82 %. No quantity is reported for the ASAP algorithm because patient preference is never taken into account under ASAP.

6 Conclusion

Managing patients in nuclear medicine departments is a very challenging problem with limited research reported in the literature. The complexity involved in this health care setting makes this problem unique. In this paper, we derive and implement algorithms for scheduling nuclear medicine patients and resources. The scheduling algorithms take into consideration the time constraints imposed by the decay of the radiopharmaceuticals, which are required for most of the nuclear medicine procedures. The algorithms were implemented within a simulation framework and the experiments performed were based on historical data provided by an actual clinic. We obtain computational results that provide useful insights into patient service management in nuclear medicine. For example, no single patient and re-

Table 8 Equipment percent (%) utilization

	ASAP		PP		COMB		FR	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Tread.(1)	71.51	0.83	59.05	0.70	71.56	0.56	71.55	0.67
Tread.(2)	71.56	0.86	58.93	0.79	71.53	0.59	71.53	0.70
TRT(1)	38.76	0.68	31.06	0.63	39.01	1.01	36.40	0.72
TRT(2)	32.17	0.49	26.38	0.48	32.20	0.57	32.00	0.83
TRT(3)	29.56	0.60	24.41	0.35	30.01	0.6	30.15	0.59
Axis(1)	77.72	0.50	64.14	0.55	77.35	0.43	76.90	0.55
Axis(2)	77.65	0.49	63.89	0.76	77.28	0.51	76.91	0.41
Axis(3)	77.35	0.48	64.05	0.73	77.44	0.48	78.55	0.61
P2000(1)	77.64	0.45	63.85	0.73	77.38	0.66	78.26	0.52
P2000(2)	77.66	0.4	63.96	0.58	77.51	0.66	78.45	0.68
P2000(3)	73.97	0.57	60.16	0.67	73.57	0.59	73.64	0.64
Mer.(1)	81.33	0.52	70.59	0.77	81.82	0.63	80.92	0.50

Table 9 Human resource percent (%) utilization

	ASAP		PP		COMB		FR	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Tech.(1)	65.41	0.74	54.42	0.66	65.22	0.62	76.88	0.54
Tech.(2)	65.22	0.48	54.04	0.78	65.30	0.53	76.88	0.40
Tech.(3)	65.31	0.44	54.24	0.50	65.26	0.72	70.79	0.76
Tech.(4)	65.47	0.39	54.31	0.77	65.61	0.67	70.40	0.54
Tech.(5)	65.49	0.73	54.68	0.79	65.92	0.68	70.26	0.59
Tech.(6)	66.00	0.52	54.78	0.40	66.00	0.57	70.59	0.57
Tech.(7)	66.39	0.43	55.10	0.72	66.23	0.65	70.13	0.75
Tech.(8)	66.51	0.64	55.41	0.78	66.44	0.67	62.07	0.80
Tech.(9)	71.79	0.83	59.28	0.71	71.84	0.56	71.83	0.67
Tech.(10)	71.84	0.86	59.16	0.80	71.81	0.59	71.81	0.70
Nurse(1)	47.30	0.38	38.27	0.51	47.30	0.71	28.00	0.52
Mangr(1)	65.19	0.64	52.69	0.67	64.77	0.65	40.70	0.67

Table 10 Average waiting time days (*Type 1*) from patient call to appointment

ASAP		PP		COMB		FR	
Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
1.81	0.35	18.74	0.74	7.92	0.28	7.59	0.26

Table 11 Percentage (%) of time patient preference is satisfied

ASAP		PP		COMB		FR	
Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
n/a	n/a	100.00	0.00	82.52	0.36	82.84	0.42

source scheduling algorithm provides the best results relative to all performance measures. Thus, it is up to the nuclear medicine clinic to decide which algorithm to use under given demand and patient/management preferences. Also, even though a pure patient preference algorithm provides the patient with the best preference ratio, the algorithm performs poorly relative to management measures.

While this work focuses on nuclear medicine, we believe it will also find generality in other health care settings. Further research include stochastic (online) optimization algorithms that take into account data uncertainties such as stochastic patient arrivals, patient no shows, equipment failures, and delayed radiopharmaceutical deliveries.

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