Using a Hybrid Simulation Model to Maximize Patient Throughput of Magnetic Resonance Imaging in a Medical Center

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Abstract: The purpose of this study is to shorten the waiting time of a patient to undergo a magnetic resonance imaging (MRI) examination as well as to increase the utilization rates of the five MRI scanners in a 2,735-bed medical center of Taiwan. We simulate the current MRI examination workflow through a hybrid simulation model, consisting of discrete event and agent-based simulations. Then, we maximize the MRI patient throughput per day with more radiographers during current business hours. For reasons of feasibility, a cost-effectiveness analysis is also conducted. AnyLogic, Excel, and SAS were used for building the simulation models and conducting the statistical analysis. The results show that providing 248 additional patient examinations with one additional radiographer employed during the 11:00 to 19:00 time frame would shorten the waiting time of a patient to undergo an MRI examination by 2.51 days, increase the utilization rate of each MRI scanner by an average of 6.15%, and bring an additional gross income of US$38,424 to US$69,169 per 31-day month.

1 INTRODUCTION

For decades, high-tech medical imaging scanners, such as magnetic resonance imaging (MRI), have been widely used in the examination, diagnosis and tracking of various diseases and in the detection of cancer stages and the determination of cancer metastasis position. With the improvement of personal health awareness and the rapid dissemination of health-related information through the Internet, people pay more attention to their health status and that of their family members than before. Precise preventive photographic examination in medical institutions or health examination centers is becoming increasingly common (Global Views, 2015, National Health Insurance Administration Ministry of Health and Welfare, 2018b).

To meet the needs of MRI examination, the number of medical imaging scanners in some countries has been increasing yearly. According to the Organization for Economic Co-operation and Development (OECD) statistics up to 2017, the U.S. has more scanners than any other European or American country, at 37.6 scanners per million people. Germany and Italy are in second and third places at 34.5 and 28.4 scanners per million people, respectively. Asia ranks first in the world with 51.7 scanners per million people in Japan, followed by 29.1 scanners per million people in South Korea. According to the statistics of the Central Health Insurance Agency of the Ministry of Health and Welfare, the number of scanners in Taiwan had increased to 226 by the second half of 2017, with approximately 9.58 scanners per million people, which is between Slovakia (9 scanners per million people) and Canada (10 scanners per million people) (National Health Insurance Administration Ministry of Health and Welfare, 2018a, The Organisation for Economic Co-operation and Development, 2017).

Although the number of MRI scanners has increased yearly, the waiting time for the examination is still too long. According to the standards in Ontario, Canada, patients with preferential treatment classifications P1 and P2 are very urgent outpatients, inpatients, and Emergency Department (ED) patients

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who should be examined immediately or within 48 hours; the classification P3 denotes emergency outpatients who should be examined in 2 to 10 days; and the classification of P4 denotes general outpatients. The waiting time for MRI examinations should not exceed 28 days. However, the average MRI waiting time for adult outpatients is 59 days (Health Quality Ontario, 2018). The waiting time in Manitoba, Canada, is approximately 68 workdays (Province of Manitoba, 2018). Taiwan currently has no similar statistics for the waiting time for MRI examination. However, the waiting time for MRI examination is still recognized as long.

In the health care management field, to understand the effects of new policies and new technology introductions, organizations may need to analyze relevant economic roles (e.g., competitors and suppliers), responses from users, and environmental impact. However, exploring the effectiveness of a new strategy by traditional techniques has its limitations. Most of the traditional techniques can only analyze data theoretically or qualitatively. Even some new strategies require actual or trial investment in human and material resources so that managers can understand the impact and determine whether a strategy deserves continued investment. To avoid the losses caused by failure after investment, many simulation analyses have been applied to ED research since 1999 (Hurwitz et al., 2014, Saoud et al., 2016). Additionally, a small number of studies have been applied to rehabilitation (New et al., 2015), orthopedics (Rohleder et al., 2011), surgery (Sobolev et al., 2011), hospitalization (Hahn-Goldberg et al., 2014), ophthalmology and radiology (Lindsköld et al., 2012, Viana, 2014). All these studies show that a good simulation model is adaptable (Paranjape, 2009) and can be adapted to practice changes as an aid to the evaluation decision before the new strategy is adopted.

A patient's waiting time for an examination in a radiology department includes the duration from when a radiology request is made in the clinic, the radiology department receives the request, the radiology department vets the request, the radiology department schedules the examination, to when the patient attends, waits and completes the examination (Olisemeke et al., 2014). Retrospective to 1987, a study simulated the daily non-admission patients through the radiology department of a large acute care hospital. This study showed that the addition of one more radiologist would lead to a reduction in the length of stay of non-admission patients (Klafehn, 1987).

Later studies focused on radiology department services, such as mammography (Coelli et al., 2007), sonography (Johnston et al., 2009), computed tomography (CT) (Ramakrishnan et al., 2004, van Lent et al., 2012), and X-ray (Oh et al., 2011, Lindsköld et al., 2012),. The examination process has been simulated to explore the relevant key performance indicators (KPIs) before and after the improvement plan. These studies assessed the number of patients examined within one hour, the time of completing image reports, the time of the patient waits for the examination, the length of time the patient stays in the department, and the utilization rate of the radiologist as effective indicators as to assist in the formulation and implementation of preplanning decisions (Ramakrishnan et al., 2004, Coelli et Al., 2007, Johnston et al., 2009, Oh et al., 2011). The MRI examination workflow and KPIs are different in different organizations and units. Additionally, an MRI scanner cannot provide all examination services. It depends on if the needed coil types are adopted by the scanner or not. However, a review of past studies in radiology, mostly using discrete event simulation as the main analytical method, the characteristic of patient, staff, and scanner were lack to control and define in a simulated workflow. The KPIs of the individual patient, scanner and the department could not be accurately estimated.

Hence, the purpose of the study was to propose a new strategy to maximize patients throughput so that the waiting time of a patient to undergo a magnetic MRI examination can be shortened as well as the utilization rates of MRI scanners can be increased. The specific aims in this study are (a) to develop a discrete event (DES) and agent-based simulations (ABS) model to simulate the MRI examination workflow at an MRI department in a medical center of Taiwan, and (b) to identify which time frames of day have fewer patients examined, to experiment with the proposed strategy by hiring radiographers in those time periods in the simulation model, and then to explore the changes in KPIs, including the daily MRI scanner utilization rate, monthly gross income, and waiting time to undergo an MRI examination.

2 RADIOLOGY DEPARTMENT SETTING

2.1 MRI Examination Services

The research setting was the MRI department, under the radiology department, of Taipei Veterans General Hospital (TVGH), which is a 2,735-bed medical center in northern Taiwan. This department provides MRI examination services for ED patients, inpatients, and outpatients. The MRI examination service runs

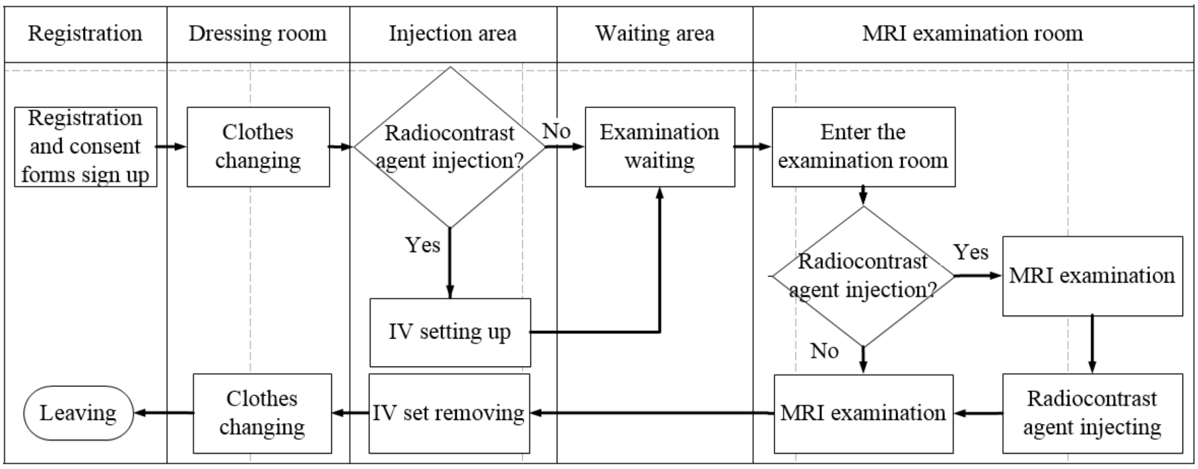

Figure 1: The patient flow of MRI examination.

from 7:30 to 23:00 on workdays and from 8:00 to 23:00 on weekends. The shifts are different for four types of human resources, including administrators, nurses, radiographers, and medical resident. The administrator and nurse only work the day shift from 8:00 to 17:30. Nevertheless, radiographers need work in either the day shift from 7:00 to 15:00 or the night shift from 15:00 to 23:00. Medical residents work shifts depending on the departmental regulations, but they are available to support the MRI examination services from 7:00 or 8:00 to 23:00, depending on the day.

The duties of each worker are as follows:

- An administrator is responsible for examination date and time scheduling, registration affairs and explanation of related matters for patients.
- Nurses are responsible for intravenous (IV) injection and assisting the administrator.
- Radiographers are responsible for MRI scanner operation and MRI examination execution.
- Medical residents are responsible for radiocontrast agent injection and the tasks of nurses when nurses are off work, i.e., before 8:00 and after 17:30.

The fixed resources of the MRI department include one 3.0 Tesla (3.0-T) MRI scanner (Scanner A) and four 1.5 Tesla (1.5-T) MRI scanners (Scanner B to E). The former is for a specific examination. Patients will be assigned to the scanner after check-in if they schedule the 3.0-T MRI service. The latter is for general examinations. Patients will be randomly assigned to one of four available scanners after check-in if they schedule for a 1.5-T MRI examination.

In the MRI department, an average of 91 patients (92 and 89 patients on weekdays and weekends, respectively) are examined a day, i.e., 18 patients for each scanner. However, the need for MRI examination service exceeds the supply. When an ED patient, inpatient, or outpatient needs an MRI examination service, he or she must wait to be examined for five hours, three days, or 30 days, respectively. The utilization rate of our five scanners ranges from 55% to 73%. Therefore, how to reduce the idle condition of the scanner and to increase the number of served patients each day warrants attention.

2.2 MRI Examination Flow

Figure 1 is the patient flow of MRI examination in the TVGH. First, patients have to check in at the registration counter and sign the consent form for MRI examinations. Then, patients walk to the dressing room to change into loose-fitting hospital clothes. If patients need a radiocontrast agent injected, the nurse will then perform the set up for intravenous placement. All patients will wait in the waiting area until the radiographer calls their names to enter the MRI examination room. Then, the patients will be examined without radiocontrast agent injection or examined before and after radiocontrast agent injection by medical residents. The examined patients with an IV set will have the IV set removed. All patients will change back into their clothes before leaving.

3 MODEL DEVELOPMENT AND EVALUATION

3.1 Simulation Framework

The simulation framework applies DES and ABS (Hamrock et al., 2013, Viana et al., 2018). The DES is used for MRI examination flow, the MRI scanners, and staffs. The ABS is applied when the patient with the different need of MRI coil types interact with each other by competing for MRI scanners. The patients have been modeled as agents to allow future development and provide a base for future expansion of the model.

As shown in Figure 2, there are two types of input parameters. One parameter is the patient attributes, and the other parameter is MRI examinations-related demand, services and resources. The former includes patients' gender, the utilized medical service types (ED patients, inpatient, or outpatients), need for a radiocontrast agent injection or not, utilized MRI scanner type (3.0-T or 1.5-T), and utilized MRI coil type (11 types). The latter includes an hourly number of patient arrivals, daily MRI examination duration time in minutes (**DailyMRIexamTime**), human resources (one administrator, one nurse, and ten radiographers), and one 3.0-T and four 1.5-T MRI scanners. For DailyMRIexamTime, if a patient needs radiocontrast agent injection, DailyMRIexamTime will encompass the injection of the radiocontrast agent as well as the coil and scanner preparation and the MRI examination execution. Otherwise, the DailyMRIexamTime includes only time in the coil and scanner preparation, and examination execution.

Output parameters are composed of four KPIs, which are the average daily utilization rates of each MRI scanner (**DailyUtiRate**, i.e., each MRI scanner's examination duration time per day divided by 16 hours), average daily overtime minutes (**DailyOverTime**), the monthly gross income (**MonthlyGrossIncome**, i.e., the increased revenue due to the increased number of patients minus the cost of the increased number of radiographers per month), and the shortened waiting time (**ShortenWaitDays**) for a patient who originally would have to wait for 30 days, i.e., an outpatient' waiting days for an MRI examination in the TVGH, to be underwent an MRI examination.

The study first built a baseline model to simulate the current MRI examination workflow in the MRI department in the TVGH. To validate if the model with simulated data is the same as the model with raw data, the Wilcoxon rank-sum test was used for comparing three input parameters and two output KPIs. The former includes a daily number of patient arrivals (**DailyNumPatients)**, the number of patients utilizing the three medical service types (**DailyNumServiceTypes**) and DailyMRIexamTime. The later includes DailyUtiRate and DailyOverTime.

After confirmation that the baseline model with simulated data has a statistically nonsignificant difference from the baseline model with raw data, we conduct experiments to build the proposed model based on the baseline model with simulated data. The proposed model is developed by adding numbers of patients and staffs per day to find an optimal DailyUtiRate with statistically nonsignificant DailyOverTime. Additionally, we not only validate that DailyOverTime has a statistically nonsignificant difference from the baseline model with simulated data, but also confirm that DailyUtiRate, MonthlyGrossIncome, and ShortenWaitDays are positive results in the proposed model.

3.2 Material and Data Preprocessing

The 2,814 MRI examination logs with de-identification of patients and radiographers in December of 2016 are collected from the MRI department. One log that belonged to the MRI examination in November is excluded. All data fields include patients' gender, utilized medical service types, need for a radiocontrast agent injection or not, utilized MRI scanner (labeled A to E), the received MRI examination name (96 classifications), and

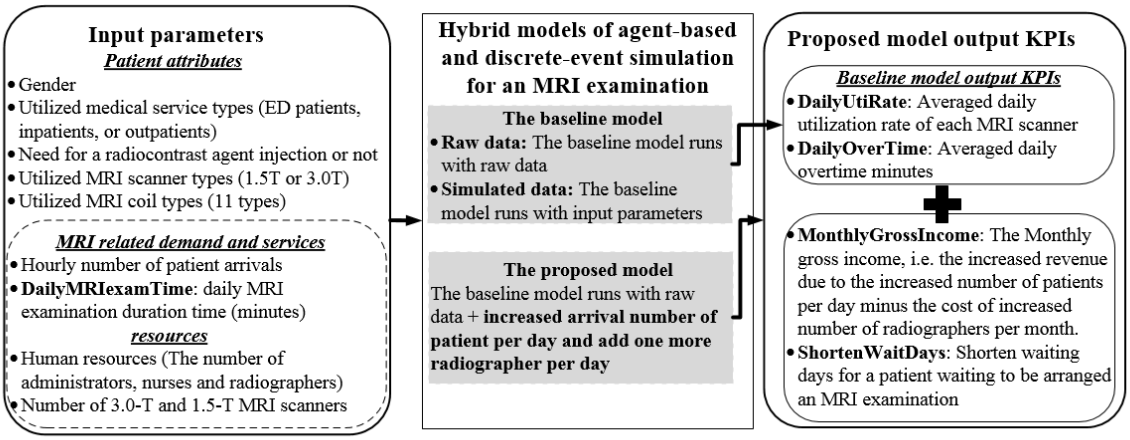

Figure 2: Simulation framework of MRI examinations workflow.

DateTime of getting on and off the MRI examination table. Other information, such as workflow, business hours, human resources allocation, the number and location of 3.0-T and 1.5-T scanners are informed by authors Sun, Wu, and Guo according to their work experience. This study was approved by the Taipei Veterans General Hospital Institutional Review Board in December 2018 (2018-01-010CC).

To generate input parameters and output KPIs, data preprocessing was conducted. To produce an hourly number of patient arrivals on each day, the study presumed that arrival time was 40 minutes before the DateTime of patients getting on the MRI examination table. Additionally, the utilized MRI scanners are converted into two types of MRI scanner types (scanner A is 3.0-T, while scanners B to E are 1.5-T). Distinct 96 MRI examination names are converted into 11 coil types. DailyMRIexamTime equals to the DateTime of getting off minus getting on the MRI examination table. DailyOverTime equals to the DateTime of getting off the MRI examination table minus 23:00.

3.3 Input Parameters

Regarding the patient attributes in the simulation models, 49.6% of patients were male, according to the raw data. The percentage of ED patients, inpatients, and outpatients are 5.6%, 19.1%, and 75.3%, respectively. Some 57.96% of all patients need radiocontrast agent injection for the MRI examination. The MRI scanner A (3.0-T) is pre-arranged for 13% of all patients, while MRI scanners B to E (1.5-T) are pre-arranged for 87% of all patients. The eleven types of MRI examination coil have different utilization rate, i.e., standard head (1.07%), torso (16.71%), shoulder (1.78%), 8-inch head (51.21%), low extremity (0.07%), neck (6.83%), torso head flexible (2.67%), breast (0.71%), spine (14.05%), cardiac (1.03%), and knee (3.88%).

The MRI examination service applies the first in, first out (FIFO) method. For each patient to be examined, the MRI scanner B, C, D, or E is arranged according to what coil type the patient needs. Each scanner's monthly examination service volume in different coil types from high to low decides the scanner's priority for the patient. For example, if the patient needs coil type "cardiac" and scanners' service volume for using the cardiac coil from high to low are scanners D, B, C, and E, the patient will be arranged to the available MRI scanner D, B, C, or E, accordingly.

For the MRI examinations-related demand, an hourly number of patient arrivals (Table 1) is calculated using the MRI examination records of December 2016. The DailyMRIexamTime for each scanner is used to generate a custom distribution. Additionally, the study adopts the thumb rule by using the triangular distribution (setting minimum, maximum and mode in minutes) for configurations of the time registration service (1,3,5), clothes changing 1,3,2), IV setting up (1,4,3), and IV set removing (1,3,2).

3.4 Output Key Performance Indicators (KPIs)

As mentioned above, MonthlyGrossIncome is estimated by the increased monthly revenue minus increased monthly cost of the proposed solution. The increased monthly revenue equals the increased number of patients multiplied by the points of the hospital global budget payment (pts) for providing each MRI examination to a patient without radiocontrast (6,500 pts) or with radiocontrast agent injection (11,500 pts) (Ministry of Health and Welfare, 2017). The monetary value of points was converted at a 0.8265 ratio and a rate of 30 Taiwanese dollars to one US dollar (National Health Insurance Committee Ministry of Health and Welfare, 2018). The increased monthly cost equals the increased number of radiographers multiplied by US$1,546, which is a market salary for a radiographer with a postgraduate degree.

3.5 The Proposed MRI Examination Model

Based on the baseline model, the study experiments with seven configurations by gradually adding even numbers of patients (i.e., 2, 4, 6, up to 14 patients) a day to the proposed model. We chose even numbers of patients because fewer patients were examined at two-time slots (i.e., 11:00, during lunch, and 17:00, during dinner) each day. To satisfy the examination needs of patients, the proposed model is designed by hiring one additional radiographer from 11:00 to 19:00 per month to provide service to these added patients.

Table 1: Number of patient arrivals per hour.

Time	6:00	7:00	8:00	9:00	10:00	**11:00**	12:00	13:00	14:00	15:00	16:00	**17:00**	18:00	19:00	20:00	21:00	22:00
Number of patients	3	6	6	6	6	**4**	6	6	7	6	6	**4**	6	6	7	5	1

3.6 The Proposed Model Validation and Analysis Tool

The simulated dates for the baseline and proposed models are from 1 December 2016 to 1 January 2017. According to the simulation framework (in section 3.1), the study tests the baseline model and the proposed model with simulated data to confirm that both have nonsignificant differences in DailyOverTime. The statistical test method used is the Wilcoxon rank sum test. The study used flow charts for workflow analysis, AnyLogic for simulation model development, Excel for exported logs of AnyLogic, and SAS for statistical analysis.

4 SIMULATION RESULTS

As shown in Table 2, the baseline model with raw data and simulated data have nonsignificant differences in DailyNumPatients, DailyNumServiceTypes, DailyMRIexamTime, DailyUtiRate, and DailyOverTime. In the raw and simulated data, DailyNumPatients are 2,813 and 2,821 patients, respectively. DailyNumServiceType, including ED patient, inpatient, and outpatient, are 5.62, 19.09, and 75.29%, respectively, in the raw data and 5.28, 19.00, and 75.72%, respectively, in the simulated data DailyMRIexamTime is 35.78 and 36.10 minutes, respectively.

Table 2: The validation of the baseline model.

Statistical parameters	Baseline model with raw data	Baseline model with simulated data	*p*-value
DailyNumPatients: *n*			
	2,813	2,821	0.6384
DailyNumServiceTypes: *n* (%)			
ED patients	158(05.62)	149(05.28)	0.7916
Inpatients	537(19.09)	536(19.00)	0.8433
Outpatients	2,118 (75.29)	2,136(75.72)	0.8820
DailyMRIexamTime: mean in minutes (standard deviation)			
	35.78(1.98)	36.10(1.38)	0.5685
DailyUtiRate: (%)			
MRI scanner A	55.10	50.41	0.1570
MRI scanner B	74.20	76.19	0.7514
MRI scanner C	74.39	75.50	0.3638
MRI scanner D	74.85	74.52	0.2050
MRI scanner E	73.35	76.22	0.3107
DailyOverTime: median in minutes (standard deviation)			
	0(42.13)	0(10.35)	0.9300

DailyUtiRate for each scanner from A to E is 55.10, 74.20, 74.39, 74.85, and 73.35%, respectively, in the raw data and 50.41, 76.19, 75.50, 74.52, and 76.22%, respectively, in the simulated data. DailyOverTime is 0 in both models.

As shown in Table 3, when the number of daily patients is increased to greater than or equal to eight patients, at least one scanner's DailyUtiRate can

Table 3: One-month simulation in the proposed model.

Experiments :Added No. of patient arrivals per day	Total No. of patients in the month	Utilization rate of the MRI scanner (daily) (%, used hours/16 hours)					Average daily overtime minutes	Added No. of radio-grapher per month	① Increased staff cost (US$) per month	② Increased point of hospital global budget payment (pts) per month (31 days)		③ Increased gross income per month (31 days) 【② x 0.8265 x 0.03US-①】		Shortened days of patient waiting to schedule an MRI examination (1 working day=16 hours)
		A	B	C	D	E				without contrast†	with contrast‡	without contrast	with contrast	
Baseline	2,821	50	76	75	74	76	6	-	-	-	-	-	-	-
+2	2,883	44	78	78	79	78	5	1	1,546	403,000	713,000	8,446	16,133	11H
+4	2,945	50	79	78	79	79	8	1	1,546	806,000	1,426,000	18,439	33,812	1D & 5H
+6	3,007	52	80	81	80	80	11	1	1,546	1,209,000	2,139,000	28,431	51,491	1D & 15H
+8	**3,069**	**53**	**81**	**83**	**83**	**81**	**15**	**1**	**1,546**	**1,612,000**	**2,852,000**	**38,424**	**69,169**	**2D & 8H**
+10	3,131	60	82	82	83	83	22	1	1,546	2,015,000	3,565,000	48,416	86,848	3D & 1H
+12	3,193	50	85	87	86	85	22	1	1,546	2,418,000	4,278,000	58,408	104,527	3D & 10H
+14	3,255	56	87	86	88	87	28	1	1,546	2,821,000	4,991,000	68,401	122,206	4D & 2H

Note: †without contrast: number of monthly patients multiplied by points of the hospital global budget payment (pts) for providing each MRI examination to a patient without radiocontrast agent injection (6,500 pts); ‡with contrast: number of monthly patients multiplied by points of the hospital global budget payment (pts) for providing each MRI examination to a patient with radiocontrast agent injection (11,500 pts).

reach more than 83%. However, only when the proposed model adding eight patients a day has a statistically nonsignificant difference in DailyOverTime (median=0 minute) compared to the raw data (p=.3257). The other experiments increase DailyOverTime.

To hire one additional radiographer will increase the cost by US$1,546 per month. The increased monthly hospital global budget payment points (income) due to MRI examination without and with radiocontrast agent injection are 1,612,000 and 2,852,000 points, respectively. As a result, MonthlyGrossIncome will be between US$38,242 and US$69,169. For a patient who originally has to wait for 30 days to be arranged an MRI examination, under this situation, the patient can be examined two days and eight hours sooner.

5 DISCUSSION AND CONCLUSION

Here, we report preliminary research on the maximization of MRI examination patient throughput. A major finding is that to hire one additional radiographer for MRI examination in the TVGH would increase the serviced volume by 248 patients a month (31 days). This proposed solution would increase the utilization rate of scanners, raise the monthly gross income, and shorten the waiting time for patients who need the MRI examination service.

Except for scanner A, the other scanners have a relatively high utilization rate. This observation is because scanner A is also used for research purposes. Compared to the discrete event-based simulation, the hybrid method can not only simulate the MRI examination workflow but also include characteristics of patients, staffs, and scanners. This characteristic makes the simulation model easy to adjust to service logic according to the agent characteristics, e.g., the utilized coil type, and lead to a nonsignificant difference from the reality.

This is also the first study in Taiwan to use simulation analysis methods to analyze and improve the evaluation of the current situation of the MRI department. In addition to proposing different opinions on improving the evaluation of the program from the traditional improvement methods, this simulation also assists the managers of the MRI department in evaluating the feasibility of the improvement program in practice and provides different decision-making aids for managers as a reference.

Despite the hybrid simulation model's advantages, it does have four limitations. First, the time stamps of patient registration, clothes changing, IV setting up and IV set removal cannot be obtained. We calculate these timestamps according to the thumb rule. Moreover, the DateTime of getting on and off the MRI examination table were manually entered into an information system by radiographers. The accuracy of our data is unknown, although the simulated model is well developed. Third, the simulation model is based on the data during December 2016. The variances due to seasonal reasons are not accounted for in the study. Fourth, the simulated model cannot be generalized to other fields. However, the study design and simulation method, including the parameters, can be a reference for related workflows, e.g., CT examinations.

This maximization of MRI examination patient throughput is still in the experimental stage, and much more work has yet to be conducted. Much more also needs to be known about how to pre-arrange patients with different coil-type needs and how to properly assign on-site patients to busy scanners. This study should provide a simulation basis for additional research. There is a continuing need for an adequate solution with big-data simulations for the practical application of MRI examination management with a high utilization rate of scanners and less waiting time for undergoing an examination.

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