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Use of the 'Queuing theory' and patient-based characteristics to assess the performance of a paediatric intensive care unit

Abstract

The performance of an intensive care unit (ICU) is the prompt admission of patients with specific conditions and institution of appropriate management leading to expected outcomes within the expected time. Therefore, assessment of ICU performance generally involves selection of appropriate indicators in patient-, institutional- and environmental- based characteristics and their application in relevant mathematical models. Unfortunately, these models are often too complex and not easy to adopt in different situations. Here, a simple method using the 'queuing theory' and patient-based characteristics to gauge the performance of a Paediatric Intensive Care Unit (PICU) is described. This was a ten year retrospective study to determine the queuing nature and patient based characteristics in the PICU using records of patients who were prescribed antibiotics from January 1998 to December 2007. The daily arrival rates and length of stay were used in the queuing simulation formula to derive the appropriate parameters. It was established that 63% of the PICU was utilised by patients who stayed for 7.48±6.8 days. The ICU admitted mainly children and infants of low body weight, with a variety of medical and surgical problems and experienced many complications while in the PICU. These patients were successfully managed, whereby most patients improved, leading to a low mortality rate of <5%. In conclusion, the queuing theory was successfully used to evaluate the performance of the PICU (ICU utilisation, type of patients admitted, common conditions and length of stay) and to recommend appropriate remedial measures. The model is simple and can be used in other ICUs.

Keywords: queuing theory, paediatric intensive care unit, performance, length of stay, arrival rate

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Riana van Wyk, Andrew Walubo

Department of Pharmacology, University of the Free State, South Africa

Correspondence: Andrew Walubo, Department of Pharmacology, University of the Free State, Bloemfontein 9300, South Africa, Tel 27-51-401-3090, Email waluboa@ufs.ac.za

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Abbreviations: APACHE, acute physiology and chronic health evaluation; ICU, intensive care unit; LOS, length of stay; MPM, mortality probability model; PICU, paediatric intensive care unit; SAPS, simplified acute physiology score; UAH, universitas academic hospital

Introduction

The performance of an intensive care unit (ICU) is the prompt admission of patients with specific conditions and institution of appropriate management leading to expected outcomes within the expected time. Such performance is influenced by patient, institutional and environmental based characteristics. Patient based characteristics include the severity of the condition, complications while in ICU, the disease pattern, number of patients and patient specific factors such as age, weight, etc. Institutional based characteristics include human resources (number and expertise), structure of the health facility, equipment, supplies and the nature of the ICU with regard to noise, ambient light, restriction of mobility and social isolation. Environmental based characteristics refer to the social-economic status and the health system of the country. In the public sector, social-economic status determines the government's ability to meet the cost of ICU care including patient support, while the health system determines the care offered in a specific ICU according to the level of hospital in the referral system. For a given ICU, institutional and environmental based characteristics are more or less static, leading to patient based characteristics being the major determinant of ICU performance.

In the same perspective, assessment of ICU performance generally involves selection of appropriate indicators in patient, institutional and environmental based characteristics and their application in relevant mathematical models. The most commonly used mathematical models include the Acute Physiology and Chronic Health Evaluation (APACHE II and III), Simplified Acute Physiology Score (SAPS) II, Mortality Probability Model (MPM) II_0 and MPM II_{24} and the customized SAPS II and MPM II_{24}.[1–6] Unfortunately, these models require selection of subjects with specific conditions, from whom appropriate clinical scores are generated and then used in the appropriate model formula.[7] Such tedious requirements and the fact that these models are more accurate in settings that are similar to those, in which they were developed,[8] have made it difficult to apply them in some ICUs, especially in the developing countries.

Therefore, there is a need for a simple method by which to gauge the performance of an ICU before embarking on models that involve extensive evaluations. It was envisaged that the 'queuing theory' could be used for a global overview of the ICU performance from which the need for further evaluations using the appropriate models can be determined. The queuing theory is the mathematical study of waiting lines or queues that enables prediction of queue lengths and waiting times at service centers.[9] Unfortunately, as indicated earlier by

McManus et al.,[10] despite the several feasibility reports supporting its potential usefulness in the various health services spots, the queuing theory has not been embraced for use in health care services[11–15] and the complex data collection and mathematical modeling used in these reports were suggested as the major drawback.[10]

Although there might be no visible queue to the ICU, there is a booking process by which patients are referred to the unit and are admitted based on a 'first-come first-serve' basis, notwithstanding that, at times, some emergencies require the severely ill to jump the queue. Therefore, to ensure that critical treatment of patients is maintained while waiting, the referring physicians need to appreciate the waiting time for admission to the ICU and such time should be reasonable. If used carefully for prediction of queue lengths and waiting times, the queuing theory can help in balancing the capacity of the ICU to provide a service within the expected time. During a study on the pattern of antibiotic use and resistance in the Paediatric Intensive Care Unit (PICU) at Universitas Academic Hospital (UAH) in Bloemfontein, South Africa, it was envisaged that a simple method for managing patient admission and ensure continuous monitoring was necessary. Here, the use of the 'queuing theory' and patient based characteristics to evaluate the performance of the PICU at UAH is described with a hope that this will contribute to identifying and understanding of factors influencing patient care in the PICU.

Materials and methods

General

This was a ten year retrospective study to determine the queuing nature and patient based characteristics in the PICU using records of patients who were prescribed antibiotics from January 1998 to December 2007. This group of patients was selected because it was part of an ongoing study on antibiotic use in the PICU and, except for an infection; these patients exhibited a variety of underlying conditions that reflected on the common problems in the PICU. Ethical approval was obtained from the Ethics Committee of the Faculty of Health Sciences, University of the Free State and permission was obtained from UAH management.

Procedure

Patients admitted during the stated period were identified from the admission list of the PICU. The hospital numbers for these patients were used to access the patient records in the hospital. The records were checked for selection of patients who met the inclusion criteria, i.e. patients who were admitted to the PICU during the study period and were treated with systemic antibiotics. Thereafter, the patient information was recorded on a data collection sheet. This information was later transferred to an Excel® datasheet where an alternative form of identification was used to protect the patient's identity. However, to determine whether the information addressed in the data collection sheet was available, a pilot study on ten patients' records was undertaken. From this, the relevant indicators/parameters of patients' information were selected and the data collection sheet was revised accordingly. Data collected included admission information (date of admission and discharge, referral source and outcome, etc.), personal information (age, gender, weight, etc.) and problems on admission and during stay in the PICU (complications, invasive devices and surgical procedures performed while in the PICU).

Statistical analysis

Data was analyzed using GraphPad InStat® statistical software of the Department of Pharmacology. Results were summarised using descriptive statistics and where applicable, non-parametrical statistical methods (Mann Whitney U-test) were used for comparison of data with the level of significance at $p<0.05$.

Evaluation of the PICU performance using the queuing theory

The use of the queuing theory requires first identifying the appropriate queuing model for the ICU. During admission to the ICU, patients are distributed to the different available beds (Channels) and they are served on the allocated respective beds only (one service point). Furthermore, the number of patients to be served is not known (infinite) and they are served on a first come first serve basis. As such, the appropriate queuing model for the ICU is a "Multi-channel, Single phase model (M/S/1), from an Infinite population, with Poisson distribution arrival pattern, an exponential probability service pattern and are served a 'first come first serve basis. Therefore, further evaluation by the queuing theory requires first determining the 'type of server', the daily arrival rates and service times in the PICU. This is because the daily arrival rates and service times in the PICU must be tested and proven to exhibit Poisson distribution and exponential probability distribution characteristics, respectively, in order for the queuing theory to be applicable.[9] A Poisson distribution describes a process in which events occur continuously and independently at a constant average rate, while exponential probability distribution describes the time between events in a Poisson process. In the ICU setting, service time is synonymous with the length of stay (LOS), which is also a process occurring continuously and independently at a constant average rate.

When the distribution of daily arrival rates and the LOS (service times) meet the aforementioned criteria, the queuing theory formulas can be used to derive the appropriate parameters. These include the probability of having no patient in the PICU (P_0), the average number of patients in the system (L) and in the waiting line (Lq), the average length of stay (W) as well as the overall PICU utilisation (ρ). The number of beds (m), the mean arrival rate (λ), the mean service rate (μ) and patients served per day can be calculated from the raw data and then used to derive the aforementioned parameters using the appropriate queuing theory formula as follows:

The probability that no patients are in the ICU is:

$$P_o = \frac{1}{\sum_{n=0}^{m-1} \frac{(\lambda/\mu)^n}{n!} + \frac{(\lambda/\mu)^m}{m!}\left(\frac{m\mu}{m\mu-\lambda}\right)} \ldots\ldots\ldots\ldots[I]$$

The average number of patients (L_q) in the waiting line is:

$$L_q = \frac{(\lambda/\mu)^m \lambda\mu}{(m-1)!(m\mu-\lambda)^2} P_o \ldots\ldots\ldots\ldots[II]$$

The average number of patients in the system (L), both waiting and being served:

$$L = L_q + (\lambda/\mu) \ldots\ldots\ldots\ldots[III]$$

The average time a patient spends in the system (W), same as length of stay (LOS):

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$$W = \frac{1}{\mu} = \frac{L}{\lambda} ....[IV]$$

The average time a patient spends in the queue waiting for service (W_q):

$$W_q = \frac{L_q}{\lambda} ....[V]$$

The average ICU utilization rate (ρ: proportion of patients served per bed):

$$(\rho) = \frac{\lambda}{m\mu} ....[VI]$$

Results

Admission characteristics

The PICU is a five-bed unit on the tenth floor of UAH, Bloemfontein, the only tertiary-care hospital in the Free State Province. It admits acutely ill or severe cases for acute management in a favourable environment with regard to availability of equipment, medicines and expert medical teams. Therefore, patient based characteristics were preferred for this study because they are the determinants of ICU performance whenever the environmental and institutional factors are unchanging as in this case.

Of the 1,305 patients identified from the PICU admission list over the ten-year study period, 1,221 patients' records were retrieved and, of these, 685 (56.1%) patients met the study criteria. However, because the number of patients who met the study criteria for 2002 and 2005 was small, they were considered as outliers and thus excluded from further analysis. Average admission was 85.6±12.8 patients per year (n=8), leading to a coefficient of variation of 14.95%, implying that there was no seasonal variation in admissions. Furthermore, most of the patients (64.5%) were admitted from the hospital's wards (including 41.8% via theatre), while 32.6% were admitted via casualty. Figure 1A shows the 'exponential patient distribution' for the LOS. The LOS ranged between 1 day and 65 days, with geometric mean of 5.65±0.18days versus a numeric mean of 7.48±6.77 days. Twenty-six percent (26%) of patients stayed in the PICU for 1 to 3 days, 51% for 4 to 9days and 22.3% for 10 days and longer. Regarding outcome, most patients (93.7±3.2%) recovered/improved and were discharged to hospital wards or home. On the other hand, 5±2.5 patients per year died during stay in the PICU, giving an annual average mortality rate of 5.9±2.7%.

Queuing theory

Proof of Poisson and exponential probability distribution

Type of server: Since there was more than one bed (server) available to which patients were booked for admission (waiting line), the PICU admission fitted a multiple-server system (Figure 1B). This meant that when a patient gets to the head of the line, the patient is admitted (served) to the next available bed (server).

Poisson distribution: To prove that the mean rate of arrival (λ) exhibited a Poisson distribution, the Poisson distribution formula was used as follows:

$$P(x) = \frac{\lambda^x e^{-\lambda}}{x!} ....[VII]$$

Where $P(x)$ is the Poisson distribution, $x!$ is the proposed (assumed) number of patient arrivals in the time period, λ is the actual daily arrival rate in the study sample and e is the natural log and is a constant 2.71828. The actual daily arrival rate (λ) for the study sample was the total number of patients admitted over the 8 years divided by the number of days in 8 years ≈ 1221/(360X8) = 0.424 patients per day. The daily arrival rate (λ) was then plotted against the Poisson probability (P) to illustrate the probability of having 0, 1, 2, etc. patients (assumed patients) arrive on the same day, thereby proving the Poisson distribution characteristic of the daily arrival rates (λ) (Figure 1C).

Distribution of service times: To prove that the probability (P) of a patient staying for a given time (t; LOS) exhibited exponential probability distribution, the following exponential equation was used and the resultant data is illustrated in Figure 1D.

$$P = (e)^{-\delta t} ....[VIII]$$

Where δ is the number of patients served per day (service rate) and was calculated from the raw data as 1/LOS (1/7.48)=0.134 patients per day. In effect, Figure 1D is the modeled (transformed) form of Figure 1A, but only plotted up to 18 days.

Applying the queuing theory

Since the distribution of arrivals exhibited a 'Poisson distribution' and the service times (LOS) exhibited an 'exponential probability distribution', the queuing theory formulas I to VI were used to derive the appropriate parameters. The probability that 'no patient' was in the PICU was virtually zero (0.007408; [I]). The average number of patients (L_q) in the waiting line was also zero [II]. The average number of patients in the system (L), both waiting and being served was 4 patients [III]. The average time a patient spent in the system or in the PICU (LOS) was 7.46 days [IV]. This LOS is similar to the calculated LOS (7.48). The average time a patient spends in the queue waiting for service (W_q) was zero, i.e., there was no waiting line or queue waiting for service [V]. The average PICU utilisation rate for the patients staying an average of 7.46days (ρ: bed utilisation) was 63% [VI].

Patient based characteristics

The majority of admissions (49.2%) were children 1 to 15 years of age, followed by infants (41%). There was a double fold increase in infant admissions from 19 patients in 1999 to 47 patients in 2003. Overall, 56.2% were males and 43.7% were females. All patients were underweight with infants below the 2nd percentile while the children were at the 50th percentile (Table 1).

Problems on admission

There were 1,735 problems on admission, owing to the fact that most patients (69.5%) had more than one problem on admission. By systemic grouping, the top ten groups were respiratory 23.4%, gastro-intestinal 22%, cardiovascular 19%, genito-urinary 6.2%, malignancies 6.1%, central nervous system 5.3%, haematological 4.4%, HIV 2.3%, endocrine 1.7% and musculo-skeletal 1.3% (Figure 2). Altogether the ten groups accounted for 91.7% of the presenting problems on admission.

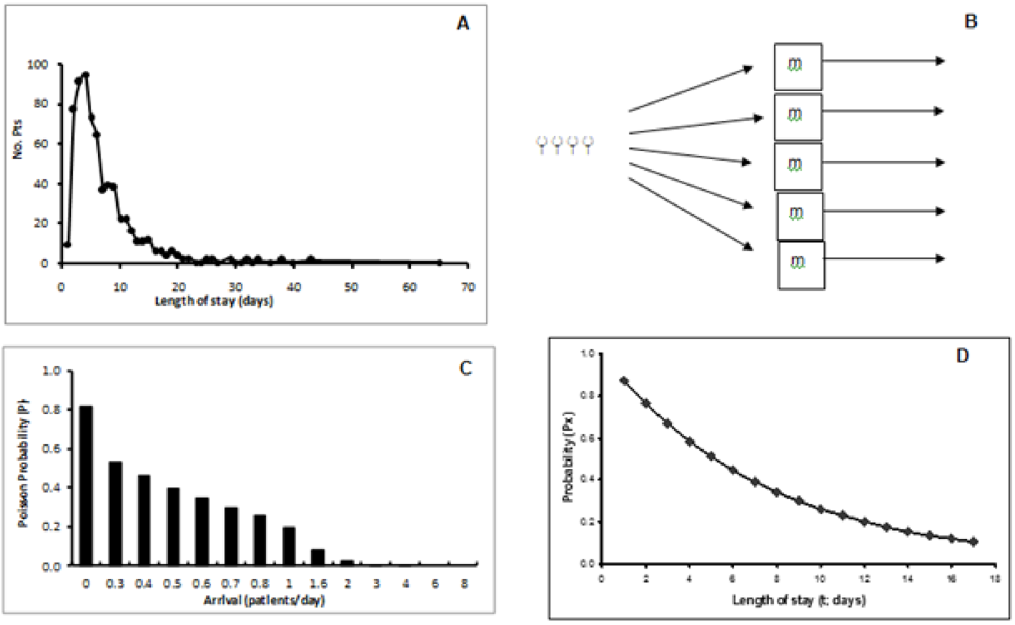

Figure 1A An illustration of exponential probability distribution for length of stay in the PICU.

Figure 1B A phase/multiple server system.

Figure 1C Poisson probability (*P*) distribution of the daily arrival rates (λ) for admissions

Figure 1D The modeled exponential probability distribution versus length of stay (*t*) up to 18days.

m = Service centre (bed).

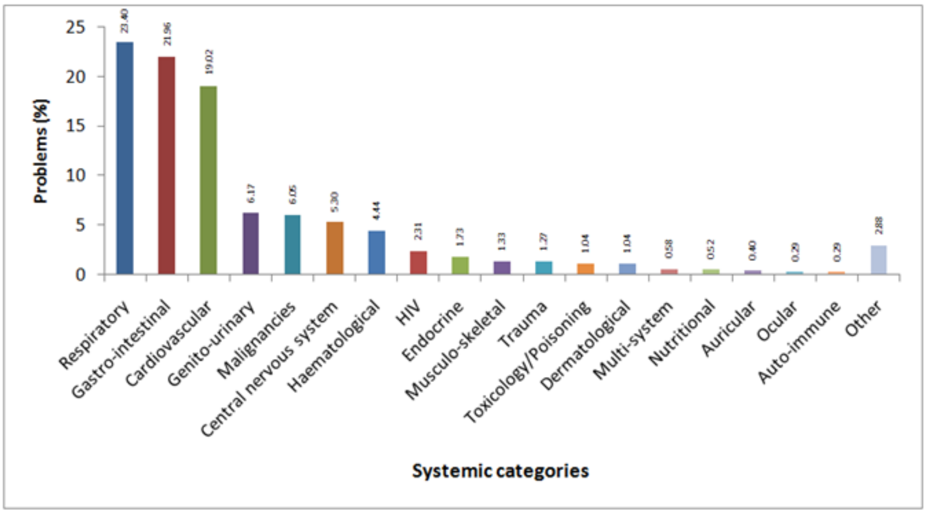

Figure 2 The proportion (%) of problems on admission by systemic category.

Table 2 is an illustration of some of the patients' conditions on admission with their frequencies per systemic category. Effectively, 60 respiratory conditions occurred 406times, whereby the most common respiratory condition was pneumonia with 38.2% prevalence, followed by respiratory obstruction, tuberculosis and tracheostomy, with a prevalence of less than 10% each. Likewise, 110 gastro-intestinal conditions occurred 381 times, with bowel obstruction accounting for 10.8%, followed by hernia 9.7% and biliary atresia, colostomy and bowel resection, with a prevalence of less than 6% each. Thirty (30) cardiovascular conditions occurred 330 times and these were largely due to congenital heart and artery defects (47%), followed by heart failure (13%) and pulmonary hypertension (9.4%). Thirty-five (35) genito-urinary conditions occurred 107 times, while 31 central nervous system conditions occurred 92 times. The genito-urinary problems were mainly due to renal failure (24.3%) and urinary tract infection (16%), while the central nervous system conditions were mainly convulsions (17.4%), hydrocephalus (16.3%), meningitis (15.2%) and neural tube defects (14.1%). Twenty-three haematological conditions occurred 77 times and were mostly due to septicaemia (65%). Of note, congenital defects accounted for 19.7%

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of the total problems on admission, of which the top five accounted for 95.1% of the congenital defects, i.e., cardiovascular (45.5%), gastro-intestinal (32.6%), central nervous system (9.4%), respiratory (4.7%) and multi-system (2.9%).

Table 1 An illustration of patients' average weight per age and the respective percentile range

Age(Months)	Males		Females	
	Weight (kg)	Percentile (%)	Weight (kg)	Percentile (%)
1	3.45(n=35)	2%	3.27(n=30)	5%
2	3.78(n=25)	<2%	3.86(n=23)	2%
3	3.84(n=22)	<2%	3.96(n=15)	<2%
6	6.48(n=8)	5%	5.99(n=13)	5%
9	6.02(n=5)	<2%	6.8(n=3)	5%
12	9.85(n=36)	50%	9.06(n=27)	50%
24	12.05(n=30)	50%	11.56(n=16)	50%
60	16.97(n=15)	50%	16.55(n=13)	50%
96	23.91(n=16)	38%	24.14(n=7)	50%
144	33.78(n=9)	20%	33.91(n=11)	20%

Table 2 An illustration of some of the patients' conditions on admission with their frequencies(f) per systemic category

Respiratory	*fa*	%	Pancreas Pseudocyst	5	1.31
Pneumonia	155	38.18	Oral Candidiasis	4	1.05
Respiratory Obstruction	40	9.85	Gastrostomy	4	1.05
Tuberculosis	17	4.19	Bowel Atresia	4	1.05
Tracheostomy	14	3.45	Gastroenteritis	4	1.05
Pleural Effusion	12	2.96	GIT Bleed	4	1.05
Croup	11	2.71	Ileostomy	4	1.05
Apnoea	9	2.22	Ladds Bands	4	1.05
Acute Respiratory Distress Synd.	9	2.22	Oesophageal Varices	3	0.79
Respiratory Distress	8	1.97	Cholangitis	3	0.79
Aspiration Foreign Object	7	1.72	Hepatitis	3	0.79
Laryngeal Papillomatosis	6	1.48	Liver Failure	3	0.79
PCP	6	1.48	Splenomegaly	3	0.79
Pneumothorax	6	1.48	Septic Ileus	3	0.79
Respiratory Failure	6	1.48	Peritonitis	3	0.79
Adenoid Hyperplasia	5	1.23	Others <3 Each	84	22.05
Adenoidectomy	5	1.23	Total	381	100
Adenotonsilectomy	5	1.23	Cardiovascular	f	%
Empyema	5	1.23	Congenital HT/art. Defect	155	46.97
Tracheitis	4	0.99	Heart Failure	43	13.03
Obstructive Apnoea	4	0.99	Pulmonary Hypertension	31	9.39
Brongiolitis	4	0.99	Pericardial Effusion	5	4.55
Bronchopulmonary Dysplasia	4	0.99	Shock	15	4.55
Chylothorax	4	0.99	Cor Pulmonale	10	3.03
Laryngomalacia	3	0.74	Hypertension	8	2.42
Retrofaringeal Abscess	3	0.74	Portal Hypertension	8	2.42

Table Continued..

Respiratory	***fa***	**%**	**Pancreas Pseudocyst**	**5**	**1.31**
Asthma	3	0.74	Infective Endocarditis	7	2.12
Chronic lung disease	3	0.74	Heart Catherization	6	1.82
Pulmonary Oedema	3	0.74	Myocarditis	5	1.52
Tamponade	3	0.74	Arterial Septostomy	3	0.91
Cyanotic Attacks	3	0.74	Others <3 Each	24	7.27
Others <3 Each	34	8.37	Total	330	100
Total	406	100	Genito-Urinary	f	%
Gastro-Intestinal	*f*	%	Renal Failure	26	24.3
Bowel Obstruction	41	10.76	Urinary Tract Infection	17	15.89
Hernia	37	9.71	Haemolytic Uraemic Synd.	8	7.48
Biliary Atresia/Kasai	19	4.99	Pre-renal Failure	7	6.54
Colostomy	18	4.72	Nefrotic Syndrome	5	4.67
Bowel Resection	13	3.41	Hydronephrosis	4	3.74
Jaundice	12	3.15	Candida Urinary Ttract Inf.	3	2.8
Anus Imperforatum	12	3.15	Glomerulonephritis	3	2.8
Hirschsprungs Disease	11	2.89	Nefrectomy	3	2.8
Liver cirrhosis	8	2.1	Others <3 each	31	28.97
Bowel perforation	8	2.1	Total	107	100
Jejenostomy	8	2.1	Central Nervous System	f	%
Pyloric Stenosis	7	1.84	Convulsions	16	17.39
Colostomy Closure	7	1.84	Hydrocephalus	15	16.3
Ascites	7	1.84	Meningitis	14	15.22
Choledochus Cyst	6	1.57	Neural Tube Defects	13	14.13
Pancreatitis	6	1.57	Brain Abscess	3	3.26
Necrotising Enterocolitis	6	1.57	Brain Infarction	3	3.26
Gastro-esophageal Reflux Disease	5	1.31	Others <3 Each	28	30.43
Oesophageal Atresia	5	1.31	Total	92	100

Problems during stay in the PICU

Problems during stay in the PICU comprised of medical complications, surgical procedures and invasive device. There were 1,875 medical complications in 507 patients (74%). By systemic grouping, the most common complications were: respiratory (28.5%), genito-urinary (17%), haematological (16%), cardiovascular (8.3%), gastro-intestinal (7.7%), central nervous system (4.2%), dermatological (3.8%) and endocrine (3.8%). On the other hand, 500 infective complications occurred in 309 (61%) patients, with the most common being pneumonia (35.6%), septicaemia (11.4%), urinary tract infections (8.8%) and wound sepsis (5.6%). Two hundred and seven (207) surgical procedures were done in 157 patients while in the PICU. By systemic grouping, the most common surgical procedures were: gastro-intestinal (32.9%), respiratory (29.5%) and cardiovascular (18.8%) and all these accounted for 81.2% of the surgical procedures done. Almost all patients (99%) had invasive devices while in the PICU. Intravenous lines were the most common (99.9%), followed by endotracheal tubes (49.9%) and urinary catheters (31.8%).

Discussion

In this study, the performance of the PICU was successfully evaluated using the queuing theory and some of the patient based characteristics. Briefly, the PICU is a 5-bed service centre of which 63% was utilised by patients who stayed for 7.48±6.77days. This implies that the remaining 37% was either empty or was utilised by patients who stayed longer, i.e., patients who stay longer is tantamount to closing a service channel (bed). It admitted mainly children and infants who presented with aggravating factors of low body weight, a variety of medical and surgical problems and a wave of complications while in the PICU. Nevertheless, these patients were successfully managed, whereby most patients improved, leading to a low mortality rate. The robustness of the queuing theory is demonstrated by the fact that the length of stay was similar to the one calculated from the raw sample data. Therefore, using retrospective data of a representative sample, information on the ICU performance was obtained without the characteristic complex prospective data collection and mathematical modeling.[11–15] It must be emphasized here that this study was not validating the use of the queuing theory in health services, which was already done[10–15] but to illustrate that the arrival rates and LOS (service rate) of a retrospective representative sample met the requirements for successful application of the queuing theory.

This snap view of the PICU performance is critical for planning, management of patients (implementation) and continuous monitoring of the PICU. In this case, the PICU can embark on a strategy to improve its performance by setting targets such as increasing ICU utilisation by patients staying for shorter period, e.g., 75% utilisation by patients staying for 5days within 2years. This can be achieved by addressing, among other things, the aggravating patient based characteristics which includes reviewing the PICU and hospital antibiotic policy, infection control methods, nutrition programme, management of patients with congenital abnormalities in their respective clinics (especially prophylactic therapy), to mention but a few. In effect, the queuing theory was used to set the targets and the patient based characteristics to guide implementation. Of note, the queuing theory does not evaluate for severity (grade) of the conditions, hence other mathematical models would need to be used if required.

The sample size was regarded as representative of the total admissions, as it covered 56.1% of the total admissions. A similar sample size (56.6%) was used in a one year prospective study of the neonatal ICU at University Children's Hospital, Zurich, Switzerland.[16] Regarding the omission of 2years (2002 and 2005), a similar approach was used successfully in a 25year study of emergency surgical admissions where study samples were taken every after 4years.[17] However, the use of patients who were on antibiotics could have led to selection of patients with the many conditions that predisposed to the development of infections, leading to a misrepresentation of the non-infected group and the PICU performance in general. Nevertheless, the fact that patients on antibiotics accounted for over 50% of the total PICU admissions and the conditions for which they were treated varied widely from medical to surgical (Figure 2), implies that the study sample reflected the true picture of the PICU. Nevertheless, this was a retrospective study that is was bound to suffer from lack of information due to unavailability and incompleteness of some records, which in some cases led to unclear diagnosis. Fortunately, a pilot study ensured that the relevant parameters were available to meet the objectives of this study.

This mathematical approach also introduced some new terminologies in the critical care field. First, a definition of 'ICU performance' was suggested. It captures the requirements for a safer health system as proposed by the USA Institute for Medicine, i.e., health care should be safe, effective, patient-centered, timely and efficient.[7] This is illustrated with these qualities interposed in the definition as follows: "The performance of an ICU is the prompt (timely) admission of patients with specific conditions (patient-centered) and institution of appropriate management (safe and equitable) leading to expected outcomes (effective) within the expected time (efficient)".

On the other hand, the factors affecting the performance of the ICU were categorized into 'patients based characteristics', 'institutional based characteristics' and 'environmental based characteristics'. Whereas the 'patient based characteristics' relate to the category of "process' proposed earlier by Donabedian,[18] both the 'institutional based characteristics and environmental based characteristics' relate to the category of 'structure'. Separation of the latter two characteristics not only enables focussing on the two issues separately, but also enables easy comparison of the performance of ICUs of a similar nature, i.e., to compare apples with apples'. Furthermore, the 'outcome' category was considered as 'the set of parameters or data from each of the three characteristics by which the ICU performance was assessed'. Similar to earlier recommendations,[19] it is advised that, in assessing ICU performance, it would be more appropriate to use critical parameters from each of the three categories that influence ICU performance. In conclusion, the queuing theory was successfully used to evaluate the performance of the PICU at UAH and to recommend appropriate remedial measures and this should be applicable to other ICUs.

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None.

Conflict of interest

The author declares no conflict of interest.

References

1. Knaus WA, Draper EA, Wagner DP. APACHE II:a severity of disease classification system. *Crit Care Med*. 1985;13(10):818–829.
2. Knaus WA, Wagner DP, Draper EA, et al. The APACHE III prognostic system. Risk prediction of hospital mortality for critically ill hospitalized adults. *Chest*. 1991;100(6):1619–1636.
3. Le Gall JR, Loirat P, Alperovitch A, Glaser P, Granthil C, et al. (1984) A simplified acute physiology score for ICU patients. *Crit Care Med*. 1984;12(11):975–977.
4. Le Gall JR, Lemeshow S, Saulnier F. A new simplified acute physiology score (SAPS II) based on a European/North American multicenter study. *JAMA*. 1993;270(24):2957–2963.
5. Lemeshow S, Teres D, Pastides H, et al. A method for predicting survival and mortality of ICU patients using objectively derived weights. *Crit MCare Med*. 1985;13(7):519–525.
6. Arabi Y, Al Shirawi N, Memish Z, et al. Assessment of six mortality prediction models in patients admitted with severe sepsis and septic shock to the intensive care unit:a prospective cohort study. *Crit Care*. 2003;7(5):R116–R122.
7. National Academy of Sciences. *Crossing the quality chasm: A new health system for the 21st century*. Washington, USA: National Academy Press; 2001.
8. Cook DA. Performance of APACHE III Models in an Australian ICU. *Chest*. 2000;118(6):1732–1738.
9. Render B. Waiting Lines and Queuing Models. In:Render B, et al. editors. *Quantitative Analysis for Management*. 11th ed. New Jersey, USA: Prentice Hall Inc; 2003. p. 561–599.
10. McManus ML, Long MC, Cooper A, et al. Queuing theory accurately models the need for critical care resources. *Anesthesiology*. 2004;100(5):1271–1276.
11. Milliken RA, Rosenberg L, Milliken GM. A queuing theory model for the prediction of delivery room utilization. *Am J Obstet Gynecol*. 1972;114(5):691–699.
12. Taylor TH, Jennings AM, Nightingale DA, et al. A study of anesthetic emergency work: I. The method of study and introduction to queuing theory. *Br J Anaesth*. 1969;41(1):70–75.
13. Tucker JB, Barone JE, Cecere J, et al. Using queueing theory to determine operating room staffing needs. *J Trauma*. 1999;46(1):71–79.
14. Scott DW, Factor LE, Gorry GA. Predicting the response time of an urban ambulance system. *Health Serv Res*. 1978;13(4):404–417.

15. El–Darzi E, Vasilakis C, Chaussalet T, et al. A simulation modeling approach to evaluating length of stay, occupancy, emptiness and bed blocking in a hospital geriatric department. *Health Care Manag Sci*. 1998;1(2):143–149.

16. Fischer JE, Ramser M, Fanconi S. Use of antibiotics in pediatric intensive care and potential savings. *Intensive Care Med*. 2000;26(7):959–966.

17. Campbell WB, Lee EJK, Van de Sijpel K, et al. A 25–year study of emergency surgical admissions. *Ann R Coll Surg Engl*. 2002;84(4):273–277.

18. Donabedian A. The quality of care. How can it be assessed? *JAMA*. 1988;260(12):1743–1748.

19. Terblanche M, Adhikari NKJ. The evolution of intensive care unit performance assessment. *J Crit Care*. 2006;21(1):19–22.