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What Can Emergency Medicine Learn From Kinetics: Introducing an Alternative Evaluation and a Universal Criterion Standard for Emergency Department Performance

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Abstract: This research focuses on developing an improved and robust measurement for emergency department (ED) performance and a criterion standard for global use via kinetic analysis.

Based on kinetic approach, the input-throughput-output conceptual model of ED crowding is compared to the procedure of enzyme catalysis. All in average, the retented patients in EDs are defined as substrate ($\bar{S}$), whereas the patients who depart the EDs as product ($\bar{P}$). Therefore, the average ED departure velocity ($\bar{V}$) can be presented as $\bar{P}$ divided by a given time (t) of the ED length of stay (LOS). The $\bar{S}$-$\bar{V}$ and $\bar{S}^2$-$\bar{V}$ plots are depicted hourly for the kinetic analysis. The long-term stability of the kinetic parameters is ascertained by the method of coefficient of variation (CV). The participants collected for this study are from the EDs of Changhua Christian Medical Center and the five branched hospitals, all located in Taiwan.

Based on the $\bar{S}$-$\bar{V}$ plot analysis, the results clearly show 2 curves, an upper and a lower curve. The timeline of the lower curve includes approximately the total ED busy hours, and thus it can be used for the subsequent kinetic analysis. In order to explore the adequate kinetic parameters for ED performance, the try-and-error process was followed in this study. As a result, the $\bar{S}^2$-$\bar{V}$ plots adapted from the lower curves show the best linear regression of $\bar{S}^2$ on $\bar{V}$ with a good coefficient of determination (R^2). The Pan-Wen constant (PW), which is the slope of the liner regression line, and the ED medical personnel unit turnover number (EDMPU TON) were deduced from the kinetic meanings of $\bar{S}^2$-$\bar{V}$ plots.

In this research, the 2 kinetic parameters, PW and EDMPU TON were applied for the ED performance evaluations. An innovative relationship between the ED retented patients and the ED departure velocity is verified as PW; whereas, a feasible kinetic parameter, the EDMPU TON explicates the teamwork efficiency of the ED providers. Moreover, the EDMPU TON may not only be a reliable universal criterion standard for the ED performance, but also a valuable reference for both ED providers and payers.

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Abbreviations: Δ = Delta, a finite increment in a variable, CMS = Centers for Medicare & Medicaid Services, CV = coefficient of variation, ED = emergency department, EDMPU = emergency department medical personnel unit, EDMPU TON = emergency department medical personnel unit turnover number, h = hour, IRB = Institutional Review Board, LOS = ED length of stay, P = product/ED departure patient, $\bar{P}$ = average product/average ED departure patient, PW = Pan-Wen constant, R^2 = coefficient of determination, S = substrate/ED retented patient, $\bar{S}$ = average substrate concentration/average ED retented patient, SD = standard deviation, t = time, TJC = The Joint Commission, V = catalysis reaction rate/ED departure velocity, $\bar{V}$ = average catalysis reaction rate/average ED departure velocity, $\bar{X}$ = sample mean.

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INTRODUCTION

Background

The emergency department (ED) performance is a vital sector for emergency medicine; the establishment of a universal standard and a robust measurement has been challenging a plethora of researchers over the last decades.[1–5] For that reason, the current methods of comparing performances from different EDs can be questionable at some points.[6–9] The key to this global issue could be the discovery of a criterion standard which can reflect the real performance of any ED.[7]

The typical measurements which have been endorsed by the regulatory bodies can detect the variations of the ED performance in certain levels.[2,4,6,10] However, this presents results for the ED performance in essential variation managements individually and retrospectively,[4] while the time efficiency issue is rarely discussed. A solution to this problem is to utilize a kinetic analysis, which will result in creating a criterion standard in order to provide a reliable estimation to ED providers, implementation plan designers, medical auditors, and health insurance payers. By applying a standard as such, more valid and practical data can be collected for ED improvement, development, innovation, as well as efficiency.

A substantial measurement of ED performance could provide the definite guidance needed, for the prevention, the mitigation, and even the preparedness phase of the emergency management of EDs.[11,12] For the healthcare systems, the real performance of EDs depends mostly on the teamwork of the ED providers[13]; in this research this workforce is introduced as ED medical personnel unit (EDMPU). Such an ED performance measurement is mainly determined by the interrelationship between the EDMPUs and the patients.

Regarding the ED performance measures and benchmarks, the summits of emergency medicine experts have proposed a set of metrics and definitions.[14,15] One major objective of the summits is to develop the consensual terms for ED patient flow and operational performance. Furthermore, Centers for Medicare & Medicaid Services (CMS) and The Joint Commission (TJC) have already commenced to incorporate ED patient flow standards in their performance measurements and accreditation programs.[16,17] In other words, the ED performance measurements can be obtained by a consistent standard or parameter deduced from the ED patient flow.[18]

It is widely accepted that a ''healthier ED'' is more efficient than a delicate ED in general, because the ED performance has an improved patient flow. Therefore, this study aims at measuring the ED performance via the efficiency analysis of the ED patient flow.

The EDs under the same pattern of management for a long period will cultivate a characterized manner for the ED operational processes with the arrival patients. The ED admitted patients are random events; yet, the ED providers render an established procedure to all the patients from arrival to departure. The flow of retented patients (S) in the ED processes can be presented physically and generally as a velocity of ED departure (V). These 2 major variants, S and V, may contain a constant which can reveal the interactions between them.

In order to discover an appropriate and reliable constant for ED performance from these 2 variants, this research applies the philosophy of the kinetics. Briefly, an interest object or phenomenon with a consistent result of performance, actions, behaviors, or functions in a large time horizon can be observed by the use of kinetic analysis. For example, during the catalysis reaction in enzyme kinetics,[19] the substrate binds to the enzyme in a confined space which results in forming products. In like manner, the ED processes are compared to the enzyme catalysis procedures; an EDMPU can be analogized as an enzyme and the retented patients as the substrate. The EDMPUs taking care of the retented patients in an ED can be related to the reaction of the enzyme binding the substrate in restricted circumstances. Therefore, the catalysis efficiency of the enzyme could be compared to the performance of the EDMPU, and the comprehensive concept of enzyme kinetics could be adopted to deduce the parameters for the ED performance evaluation.

Importance

What is the criterion standard for the ED performance and the ED efficiency? Which standard can be universal and used as a reliable reference for any ED provider, so to establish an implementation plan to improve the ED performance and the patient flow? This study presents the idea of ED kinetics and tries to contribute to the study of ED performance.

Goals of This Investigation

This study focuses mainly on 2 subjects. The first subject investigates techniques which could develop a method of kinetic studies for ED performance measurements; whereas the second attempts to determine a global criterion standard for the ED performance.

MATERIALS AND METHODS

Ethical Disclosure

The study was reviewed by the Institutional Review Board (IRB) at Changhua Christian Medical Center (IRB project no. 130303), which judged it to be exempt from further IRB review. The IRB waived the requirement for informed consent for this study.

Definitions

The definitions and terminologies follow the consensus of the ED experts in the ED performance measures and benchmarking summits.[14,15] However, certain definitions are specified to prevent ambiguous statements.

ED Departure

The physical departure of patients from the ED treatment space for all categories of patients, including admitted, discharged, observation, and behavioral health patients.

ED Length of Stay (LOS)

The duration time of patients in the ED treatment space from arrival to departure. This is tracked for the following subsets of patients: admitted, discharged, observation, and behavioral health patients.

ED Medical Personnel Unit (EDMPU)

The EDMPU is the building block of the medical personnel workforce for the ED kinetic calculations. One EDMPU can be defined as a basic unit of the ED workforce which provides certain ED medical services. In this research, 1 EDMPU is the sufficient ED workforce which can offer medical care to 1 patient per 1 working bed.

ED Working Bed

The ED beds which are practically managed by the EDMPUs to render emergency care in the ED treatment space are defined as ED working beds. For most hospitals, the ED working beds are equal to the ED licensed beds. Additionally, the ED licensed beds can be specified into several classes for different patients such as waiting in-patient beds or planning to go home. These beds would be separated from the ED treatment space in certain hospitals; however, this research focuses on the major workforce of the EDMPUs, so they will be excluded from the ED working beds.

Retented Patient

Retended patients are the patients in an ED before departing the ED treatment space regardless whatever ED process is followed.

Study Design

The input-throughput-output conceptual model of ED crowding[20] can be compared to the procedure of enzyme catalysis. Accordingly, patients are analogized as substrates during the input stage. For the throughput stage, as the substrate is subjected to the enzyme for a specific catalytic reaction, equally, the patients are given medical treatment in EDs by the EDMPUs. In the output stage, the products, which are the modified substrates, separate from the enzymes, same way as the retented patients depart from the ED treatment spaces. A proposed relationship between the enzyme-catalyzed process and the input-throughput-output conceptual model is depicted in Figure 1.

The kinetic analysis of EDs is focused on the 2 major variants of the ED retented patients (S) and the ED departure velocity (V) as it is suggested by Michaelis-Menten equation.[21] For the throughput stage, the retented patients in EDs are defined as substrate as in enzyme kinetics, whereas the patients who depart the ED treatment space (P) as product. Therefore, the V can be presented as P divided by a given time (t) of the LOS. The average S, V, and P are represented by $\bar{S}$,$\bar{V}$, and $\bar{P}$, respectively. In the kinetic procedure, an independent event is delimited by an observed hour so a time series from 0 to 23 represents 24 independent events in a day for both $\bar{S}$ and $\bar{V}$.

Setting and Selection of Participants

The participants collected for this study are from the EDs of Changhua Christian Medical Center and the 5 branched hospitals; Erlin, Lukang, Nantou, Yumin Hospital, and Yunlin Christian Hospital, all located in Taiwan. The participants are real cases without any contrived screening. The total number of the collected cases and the background information of each related ED are shown in Table 1.

Data Collection and Processing

The database of the electronic medical records of every ED is collected and retrieved for the patients' ED arrival and departure time for the period between 2010 and 2013. The arrival time starts being recorded when the patients are first contacted by the ED staff, while the departure time is being recorded after the disposition decision is completed by the physicians for the physical departure of a patient from an ED treatment space. In order to analyze the ED kinetics, each daily record of 2010 is classified hourly into series from 0 to 23, and then the $\bar{S}$ and $\bar{V}$ in an observed hour of the whole year are calculated for plot analyses. The S for a certain hour is the number of the retented patients in the EDs, regardless if they were boarded in different hours. More specifically, the S is the sum of the ED remaining patients at the beginning of a certain hour and all the new arrivals for this hour. The velocity equation is defined as $\bar{V} = \bar{P}/t$, where t is an exact hour; in this research, t is restricted to 1. The results of S and V for an exact hour are subjected to trim the outliers by applying the Z-score method.[22,23] The outliers are trimmed beyond the range of $-3 < Z < 3$; therefore, the S and V outliers will be excluded from the $\bar{S}$ and the $\bar{V}$ calculations. The percentage of outliers in S and V is less than 2% for all cases.

Primary Data Analysis

Plot Analysis

For the first time, the $\bar{S}$-$\bar{V}$ plots are applied to expound the ED kinetics; the $\bar{S}$-$\bar{V}$ plots of the 6 hospitals are shown in Figure 2. These diagrams indicate patterns of closed cycles in time series which could be separated to an upper and a lower curve at the 2 critical end points of 6th- and 22nd hour. Additionally, the ED busy hours can be observed since the patient arrivals exceed the patient departures in a certain hour via the boxplot analysis. The lower curve of the $\bar{S}$-$\bar{V}$ diagrams is appropriate for ED performance investigations, because the time period from the 6th- to the 22nd-hour covers the whole spectrum of the ED busy hours in general. This study focuses on

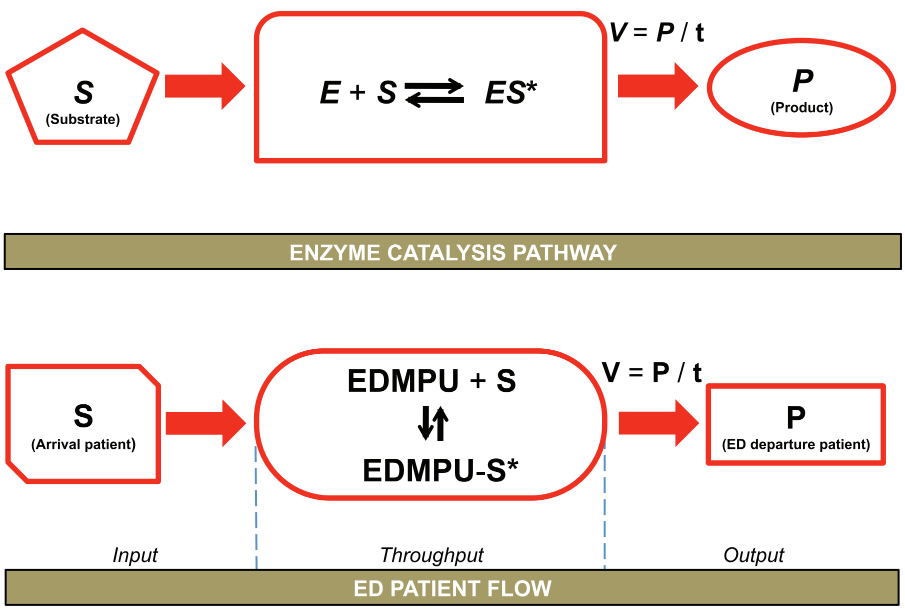

FIGURE 1. The comparisons between the enzyme catalysis pathway and conceptual model of ED crowding. The transient state of both models is indicated as "∗," while symptoms in enzyme catalysis pathway are presented in an italic style. E, enzyme; ED, emergency department; EDMPU, emergency department medical personnel unit; P, product/ED departure patient; S, substrate/retented patient; t, time; V, catalysis reaction rate/ED departure velocity.

TABLE 1. Background Information and Collected Cases of the 6 Emergency Departments

ED-Related Hospital	Hospital Level*	EMS Hospital Classification†	Collected Cases‡	ED Working Beds
Changhua Christian Medical Center	Academic medical center	Emergent	100,303	37
Erlin Christian Hospital	Metropolitan	Urgent	25,204	19
Lukang Christian Hospital	Local community	Urgent	40,984	8
Nantou Christian Hospital	Local community	Nonurgent	17,377	5
Yumin Hospital	Local community	Urgent	34,143	7
Yunlin Christian Hospital	Metropolitan	Urgent	26,902	12

ED = emergency department, EMS = Emergency Medical Service.
* In Taiwan, hospitals are basically classified into 3 levels: Local community hospitals, metropolitan hospitals, and academic medical centers, by their medical service quality and quantity.
† According to the ''Emergency Medical Service Act'' in Taiwan, the responding hospitals of Emergency Medical Service (EMS hospitals) were divided into 3 categories: emergent, urgent, nonurgent by the ''Hospital emergency medical capability classification standard'' which was announced by the Department of Health.
‡ The ED cases were collected in 2010.

that specific time period to deduce all the kinetic parameters in the subsequent experiments. More specifically, the data of the lower curve were examined by the try-and-error method to establish a linear relation between $\bar{S}$ and $\bar{V}$. Based on the findings of the $\bar{S}$-$\bar{V}$ plots, a hyperbolic trend of the lower curve is detected, therefore, a square transformation of $\bar{S}$ is applied for the $\bar{S}^2$-$\bar{V}$ plots. These $\bar{S}^2$-$\bar{V}$ plots presented the highest kinetic potential and were chosen for further studying.

The Pan-Wen Constant (PW)

The Pan-Wen constant (PW) is defined as the slope value of the linear regression line in the $\bar{S}^2$-$\bar{V}$ plots; where the physical unit of PW is (person h)$^{-1}$. On the statistical aspect, the mathematical correlation between the two variants, $\bar{S}^2$ and $\bar{V}$, can be assessed by the value of the coefficient of determination (R^2). If the linear regression of the $\bar{S}^2$-$\bar{V}$ plots shows a high R^2, the relationship between $\bar{S}^2$ and $\bar{V}$ can result in a more reliable constant. The ratio of $\Delta\bar{V}/\Delta\bar{S}^2$ is the slope of the linear regression line for the PW computing.

EDMPU Turnover Number (EDMPU TON)

In ED kinetics, the EDMPU turnover number (EDMPU TON) is defined as the maximum number of clearance of 1 working bed in an observed hour by 1 EDMPU for all categories of patients in saturated condition. In a theoretical scenario, when the saturated patients arrive in an ED, 1 working bed will be occupied by 1 patient; however, an EDMPU is sufficient enough to offer medical service per occupied ED working bed. Depending on the physical meaning of the EDMPU TON, the value of the EDMPU TON can be formulated as (PW) × (ED working bed) × (EDMPU/ED working bed); where the physical unit can be modified as: $[\text{person h}]^{-1} \cdot \text{bed} \cdot [\text{person} \cdot (\text{bed})^{-1}] = \text{h}^{-1}$. The computation of EDMPU TON is analogized to the calculation of enzyme turnover number.

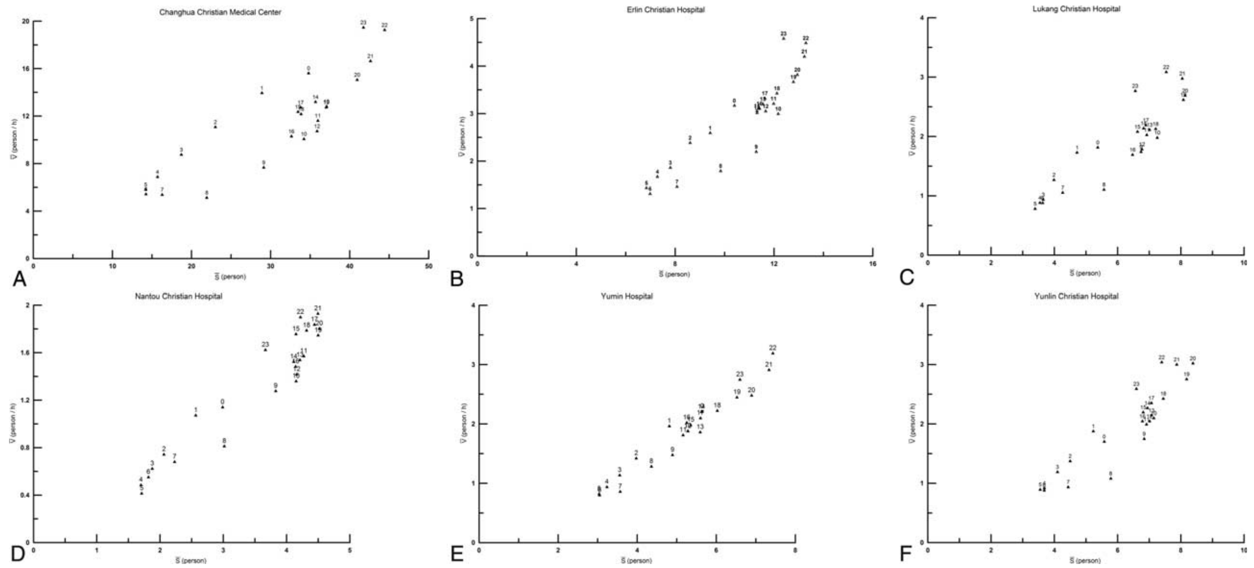

FIGURE 2. The $\bar{S}$-$\bar{V}$ plot analyses for the 6 EDs (Panels A–F) in 2010. The daily time series are characterized by numbers above the symbol in the plots. $\bar{S}$, average retented patient; $\bar{V}$, average ED departure velocity.

Statistic Analysis

The method of linear regression is applied to the $\bar{S}^2$-$\bar{V}$ plots for modeling the relationship between $\bar{S}^2$ and $\bar{V}$. If the ED retented patients have a square effect on the ED departure velocity persistently, a good R^2 (near 1) will be achieved from the linear regression line to present the robust and recurrent relationships between these 2 terms.

For a 4-year analysis, each PW can be obtained annually from the $\bar{S}^2$-$\bar{V}$ plots. The coefficient of variation (CV) is used to estimate the degrees of the dispersion of the different PW sets.[24] Furthermore, $CV = SD/\bar{X} \times 100\%$, where SD is the standard deviation and $\bar{X}$ is the sample mean. If the value of the CV is low, the PW is a robust and steady constant under a relative stable internal and external ED environment.

RESULTS

The $\bar{S}$-$\bar{V}$ plots clearly show closed cycles in time series which could be separated to an upper and a lower curve at the two critical end points of the 6th- and the 22nd-hour (Figure 2). Approximately, the lower curve elevates gradually in a 17-hour series from 6 to 22, while the upper curve decreases in a top-down manner from 23 to 5. However, a disorganized node is observed in the lower curve from 10 to 18.

The ED busy hours could be defined as the observed time period where the ED arrivals exceed the ED departures. As Figure 3 shows, the time period of 6 to 22 reveals the phenomenon of ED busy hours. This time period could be analogized with the lower curve of the $\bar{S}$-$\bar{V}$ plots. Based on the hyperbolic trends in the lower curves of the $\bar{S}$-$\bar{V}$ plots, a square transformation of $\bar{S}$ is applied for the $\bar{S}^2$-$\bar{V}$ plot analyses. The linear regression line of the $\bar{S}^2$-$\bar{V}$ plots present a good R^2 (Figure 4; Table 2) which indicates a specific interaction between $\bar{S}^2$ and $\bar{V}$; therefore the $\bar{S}^2$-$\bar{V}$ plots are suitable and accessible for subsequent kinetic analysis.

The EDMPU TON and other relative parameters are shown in Table 2. As a criterion standard of ED performance, the EDMPU TON of Yunlin Christian Hospital's ED is the highest ($0.4176\,h^{-1}$) than the other 5 on patient flow promotion. Although Changhua Christian Medical Center is the largest ED among these 6, the EDMPU TON is $0.2812\,h^{-1}$. The result indicates that the ED performance using the kinetic criterion standard of EDMPU TON is ED size-independent. This finding will break the conventional thinking of hardware- or personnel-based accreditations for ED performance. In order to evaluate the stability of PW, a statistic measure of CV can be applied for detecting the fluctuation of PW in a long-term observation. For a 4-year investigation, the CVs of the PW sets for the 6 EDs are shown in Table 3 and Figure 5 (see eTable 1 and eTable 2, Supplemental Content, http://links.lww.com/MD/A768, which present the values of the R^2 and PW in 2011–2013, respectively). The acceptable threshold of CV can be empirically considered under 20%; however, only the CV of Erlin Christian Hospital is slightly over this threshold (20.84%), while the CV of Changhua Christian Medical Center is even lower to 3.10%.

DISCUSSION

The pilot kinetic approach was conducted for the study of ED performance while a promising cycle was discovered to reveal the relationship between $\bar{S}$ and $\bar{V}$. This relationship implicates that the ED retented patients may act as a critical factor for ED performance analysis.[10] Moreover, this cycle elaborates the accelerating and decelerating phenomena in ED process hourly.

In this research, the values of $\bar{S}$ and $\bar{V}$ of the kinetic measurements for a period of 1 year are considered to attain a dynamic equilibrium between ED providers and patients. According to Figure 3, a time period of 6 to 22 represents adequately the ED busy hours and the optimization hours for the ED performance evaluations; this time period is applied for all the assessments of this research. The variants of $\bar{S}^2$ and $\bar{V}$, show a high linear correlation ($0.8272 < R < 0.9365$) in the $\bar{S}^2$-$\bar{V}$ plots of 2010; therefore, the value of the regression line slope, PW, can be

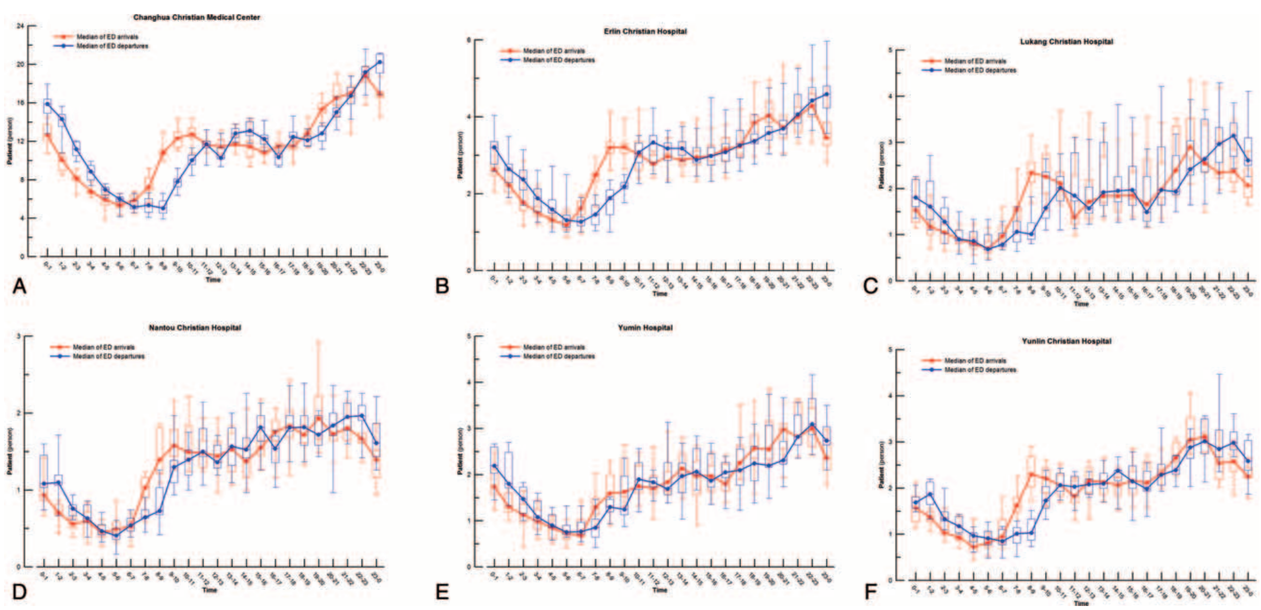

FIGURE 3. The boxplot analyses for the 6 ED arrivals and departures in an observed hour for 2010. In order to improve the readability of the boxplots, the ED arrivals and departures are averaged monthly for every observed hour before they are applied in the boxplots. The medians of the ED arrivals are linked in red lines and the departures in blue.

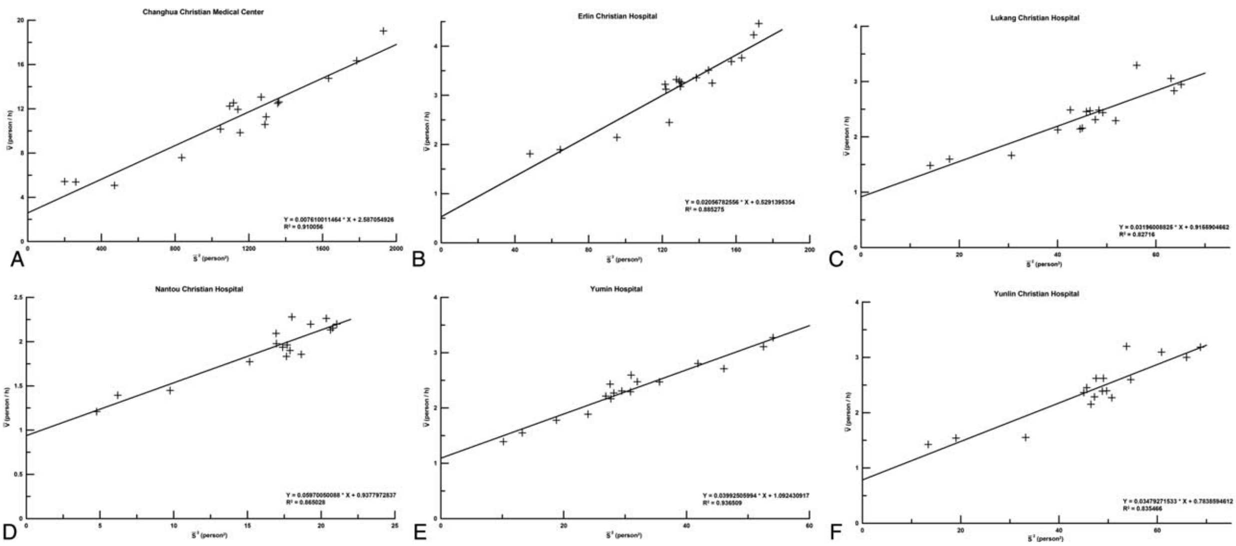

FIGURE 4. The $\bar{S}^2$-$\bar{V}$ plot analyses for the 6 EDs (Panels A–F) in 2010 with a truncated time period of 6 to 22. The linear regression lines and R^2 are depicted in the plots. $\bar{S}$, average retented patient; R^2, the coefficient of determination; $\bar{V}$, average ED departure velocity.

considered as a reliable kinetic constant for further estimations. It must be noticed that this constant states that the retented patients have a square effect on the departure velocity. The physical unit of PW is $(\text{person h})^{-1}$, which is the inverse ratio of the product of the patient number and the spent time for patient departure. That is to say, the ED providers adjust the time spent on the patients accordingly; if the patient numbers are high, less LOS can be provided by the EDMPUs, whereas, if the patient numbers are low, more LOS can be offered. Time adaptation could be one of the fundamental components of ED kinetics.

However, can the PW of an ED maintain a permanent and a persistent nature? In order to answer this critical question, the 6 EDs have been monitored for a period of 4 years, from 2010 to 2013, to detect the reliability of the linear regression model of $\bar{S}^2$ and $\bar{V}$. The PW for every ED is based on a good linear correlation and regression of the $\bar{S}^2$-$\bar{V}$ plots. The R^2 of the linear regression lines of each ED for 4 years is shown in Table 2 and eTable 1 (see the Supplemental Content), http://links.lww.com/MD/A768. The values of R^2 of all the EDs are kept in a high level during the whole study period, fact which verifies that the linear regression lines are reliable and stable for the PW computation. Therefore, the PW as a fundamental element for ED performance evaluation is robust and trustworthy.

As the 4-year data (Figure 5) indicate, the PW of Changhua Christian Hospital shows a relatively low CV (3.10%). Moreover, for the remaining 5 branched hospitals the PW shows that all the CVs are lower than 21%, which can be an acceptable deviation from mean to reveal a minor dispersion among the data sets. In addition to this, the invariability of the PW may imply the invulnerability of an ED; this could be determined by another comprehensive study.

Another important kinetic parameter in this study is the EDMPU TON, which provides a kinetic measurement and establishes a criterion standard for an ED performance across different hospitals and countries. The EDMPU TON is the unique constant of an individual ED, regardless the grade of the ED. As the results showed, the ED of the Yunlin Christian Hospital has the highest value of EDMPU TON, even if this is not the largest ED compared to the remaining 5. Besides the workforce and the hardware of an ED, an efficient EDMPU TON could result in a well-managed patient flow and the improved implementation plans.

In order to discover the impacts of the trucked time period in ED performance analysis, the $\bar{S}^2$-$\bar{V}$ plots for the time period of 0 to 23 in 2010 are investigated and compared in eFigure 1, http://links.lww.com/MD/A768 in the Supplemental Content.

TABLE 2. The Kinetic Parameters of the 6 Emergency Departments in 2010

ED-Related Hospital	PW [(person h)$^{-1}$]	EDMPU TON (h^{-1})	R^2
Changhua Christian Medical Center	0.0076	0.2812	0.9101
Erlin Christian Hospital	0.0206	0.3914	0.8853
Lukang Christian Hospital	0.0320	0.2560	0.8272
Nantou Christian Hospital	0.0597	0.2985	0.8650
Yumin Hospital	0.0399	0.2793	0.9365
Yunlin Christian Hospital	0.0348	0.4176	0.8355

All data are obtained from the ED kinetic measurements using a truncated time period of 6 to 22.

ED = emergency department, EDMPU TON = emergency department medical personnel unit turnover number, PW = the Pan-Wen constant, R^2 = coefficient of determination.

TABLE 3. The CV Calculations for the PW Sets of the 6 Emergency Departments During 2010 to 2013

	PW		
ED-Related Hospital	**Mean [(person h)$^{-1}$]**	**SD [(person h)$^{-1}$]**	**CV (%)**
Changhua Christian Medical Center	0.0079	0.00025	3.1006
Erlin Christian Hospital	0.0200	0.00416	20.8442
Lukang Christian Hospital	0.0274	0.00415	15.1507
Nantou Christian Hospital	0.0532	0.00919	17.2782
Yumin Hospital	0.0324	0.00585	18.0434
Yunlin Christian Hospital	0.0313	0.00548	17.5378

All data are obtained from the ED kinetic measurements using a truncated time period of 6 to 22.
CV = coefficient of variation, ED = emergency department, PW = the Pan-Wen constant, SD = standard deviation.

The eFigure 1, http://links.lww.com/MD/A768 can also indicate a specific interaction between $\bar{S}^2$ and $\bar{V}$ by a fair R^2. Nevertheless, considering the performance aspect of EDs, the evaluation in busy hours is more objective for ED providers, because the efficiency of EDMPU should be at the highest level during this time period. From a kinetic viewpoint, the velocity directions of the upper curves are opposed to the lower curves; therefore, a diminished consequence of an ED performance evaluation will be obtained by using the time period 0 to 23 via the $\bar{S}^2$-$\bar{V}$ plot analyses. This can be proved by the notable reduction in most EDMPU TONs of 2010 from the EDs of Changhua Christian Medical Center, Erlin Christian Hospital, Lukang Christian Hospital, Nantou Christian Hospital, Yumin Hospital, and Yunlin Christian Hospital which is 10.11%, 14.08%, 12.50%, 5.36%, 0.00%, and 14.94%, respectively. For these reasons, the lower curve of the $\bar{S}$-$\bar{V}$ plots can be employed rationally to the intensive $\bar{S}^2$-$\bar{V}$ plot analyses and kinetic evaluations.

According to the findings, the EDMPU TON is highly suggested to be a criterion standard for an ED performance evaluation because this kinetic parameter presents a long-term constant manner for ED operating processes to reveal the accustomed efficiency of the EDs. The EDMPU TON is a more accessible approach for the ED providers, since the input data such as the patient arrival time, the ED departure time, and the ED working beds use a standardized metric for every ED internationally.

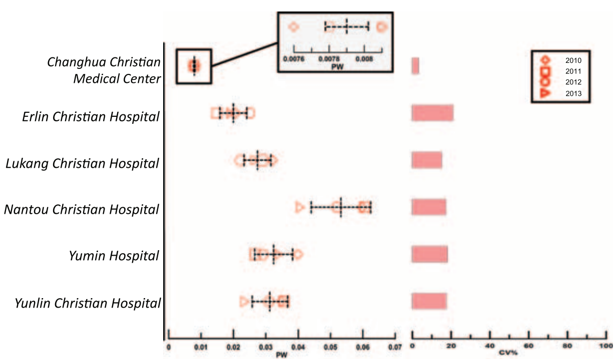

FIGURE 5. The stability analyses of PW in 2010 to 2013 for the 6 emergency departments; the CV of PW is depicted in the histogram. The bars in the PW plots represent (mean ± standard deviation). CV, coefficient of variation; PW, the Pan-Wen constant.

How the ED providers benefit from the EDMPU TON to measure the ED performance? The EDMPU TON is obtained from a long-term observation of the ED efficiency; therefore, it presents a more reasonable ''health condition'' of an ED in terms of ED performance. If the EDMPU TON can be collected by the peer level of EDs, the ED providers will be aware of the performance of their ED among the ED cohort. The EDMPU TON provides various and improved features for ED performance evaluations, such as a long-term kinetic observation for robust results, a precise physical meaning on efficiency analyses, an accessible input data for computing, and a consensual metric for international applications. Conclusively, the EDMPU TON as a criterion standard could be suggested to ED performance accreditations for global use.

LIMITATIONS

The prime limitation of this research is the selection of the time period 6 to 22, whereas the other approximate time periods are not discussed in this research. Based on statistic data, patients tend to visit EDs more frequently during the time period 6 to 22, which is sufficient to expound the kinetic features for ED performance analysis. The time period 6 to 22 represents the majority of countries and cultures; yet it is not absolute. Therefore the time period can be changed in accordance to the statistic data of each ED.

The PW of EDs can be affected by various factors; such as the medical personnel replacement, a new management policy, internal or external environmental modifications. However, the influence level on the PW of those factors could be proven by other researches. Other delicate curve-fitting methods may be applied to the PW extraction as well; however, the $\bar{S}^2$-$\bar{V}$ plot analyses are more reachable in practice.

Although the EDMPU TON is a potential ED kinetic parameter, it cannot completely solve every issue for the ED performance. Additional aspects of the ED performance estimations[4,6,25–28] can also be used to validate the reliability of the EDMPU TON and vice versa.

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REFERENCES

1. Sørup CM, Jacobsen P, Forberg JL. Evaluation of emergency department performance-a systematic review on recommended performance and quality-in-care measures. *Scand J Trauma Resusc Emerg Med.* 2013;21:62–76.
2. El-Eid GR, Kaddoum R, Tamim H, et al. Improving hospital discharge time: a successful Implementation of Six Sigma methodology. *Medicine.* 2015;94:e633.
3. El Sayed MJ, El-Eid GR, Saliba M, et al. Improving emergency department door to doctor time and process reliability: a successful implementation of lean methodology. *Medicine.* 2015;94:e1679.
4. Improving patient flow and reducing emergency department crowding: a guide for hospitals. October 2014. Agency for Healthcare Research and Quality, Rockville, MD. Available at: http://www.ahrq.gov/research/findings/final-reports/ptflow/index.html (accessed November 5, 2014).
5. Eitel DR, Rudkin SE, Malvehy MA, et al. Improving service quality by understanding emergency department flow: a White Paper and position statement prepared for the American Academy of Emergency Medicine. *J Emerg Med.* 2010;38:70–79.
6. Schuur JD, Hsia RY, Burstin H, et al. Quality measurement in the emergency department: past and future. *Health Aff.* 2013;32:2129–2138.
7. Asplin BR. Measuring crowding: time for a paradigm shift. *Acad Emerg Med.* 2006;13:459–461.
8. Asplin BR, Magid DJ. If you want to fix crowding, start by fixing your hospital. *Ann Emerg Med.* 2007;49:273–274.
9. Urgent Matters Learning Network II: Standardized Performance. Measurement and Reporting in Emergency Departments. Washington, DC: George Washington University; 2010:Available at: https://smhs.gwu.edu/urgentmatters/sites/urgentmatters/files/Standardized%20Performance%20Measurement%20and%20Reporting%20in%20ED.pdf (accessed October 10, 2015).
10. White BA, Biddinger PD, Chang Y, et al. Boarding inpatients in the emergency department increases discharged patient length of stay. *J Emerg Med.* 2013;44:230–235.
11. Emergency Management Principles and Practices for Health Care Systems, Unit 1. 2nd ed. Washington, DC: ICDRM, GWU for VHA, US VA; 2010: Available at: https://www.gwu.edu/∼icdrm/publications/PDF/EMP&P_Unit%201%202nd%20edition.pdf (accessed October 10, 2015).
12. Emergency management principles and practices for health care systems, Unit 5. 2nd ed. Washington, DC: ICDRM, GWU for VHA, US VA; 2010.
13. Institute for Healthcare Improvement. Science of Improvement: Forming the Team. Available at: http://www.ihi.org/resources/Pages/HowtoImprove/ScienceofImprovementFormingtheTeam.aspx (accessed October 18, 2014).
14. Welch S, Augustine J, Camargo CA, et al. Emergency department performance measures and benchmarking summit. *Acad Emerg Med.* 2006;13:1074–1080.
15. Welch SJ, Asplin BR, Stone-Griffith S, et al. Emergency department operational metrics, measures and definitions: results of the second performance measures and benchmarking summit. *Ann Emerg Med.* 2011;58:33–40.
16. Joint Commission on Accreditation of Healthcare Organizations. A comprehensive review of development and testing for national implementation of hospital core measures. 2006; Available at: http://www.jointcommission.org/assets/1/18/A_Comprehensive_Review_of_Development_for_Core_Measures.pdf (accessed October 10, 2015).
17. Glickman SW, Schulman KA, Peterson ED, et al. Evidence-based perspectives on pay for performance and quality of patient care and outcomes in emergency medicine. *Ann Emerg Med.* 2008;51:622–631.
18. Miro O, Sanchez M, Espinosa G, et al. Analysis of patient flow in the emergency department and the effect of an extensive reorganisation. *Emerg Med J.* 2003;20:143–148.
19. Marangoni AG. Enzyme Kinetics: A Modern Approach New Jersey: John Wiley & Sons; 2003:1–60.
20. Asplin BR, Magid DJ, Rhodes KV, et al. A conceptual model of emergency department crowding. *Ann Emerg Med.* 2003;42:173–180.
21. Michaelis L, Menten ML. Die kinetik der invertinwirkung. *Biochem Z.* 1913;49:333–369.
22. Shiffler RE. Maximum Z scores and outliers. *Am Stat.* 1988;42:79–80.
23. Wilcox RR. Applying Contemporary Statistical Techniques. California: Academic Press; 2003:76–84.
24. Reed GF, Lynn F, Meade BD. Use of coefficient of variation in assessing variability of quantitative assays. *Clin Vaccine Immunol.* 2002;9:1235–1239.
25. Gardner RL, Sarkar U, Maselli JH, et al. Factors associated with longer ED lengths of stay. *Am J Emerg Med.* 2007;25:643–650.
26. Arkun A, Briggs WM, Patel S, et al. Emergency department crowding: factors influencing flow. *West J Emerg Med.* 2010;11:10–15.
27. Sun BC, Hsia RY, Weiss RE, et al. Effect of emergency department crowding on outcomes of admitted patients. *Ann Emerg Med.* 2013;61:605.e606–611.e606.
28. Weiss SJ, Ernst AA, Nick TG. Comparison of the National Emergency Department Overcrowding Scale and the Emergency Department Work Index for Quantifying Emergency Department Crowding. *Acad Emerg Med.* 2006;13:513–518.

Supplemental Content

eTable 1. The values of R^2 on the $\overline{S}^2$-$\overline{V}$ plot analyses for the six emergency departments in 2011 to 2013

ED-related Hospital	R^2		
	2011	2012	2013
Changhua Christian Medical Center	0.8758	0.8645	0.8666
Erlin Christian Hospital	0.7835	0.8468	0.6541
Lukang Christian Hospital	0.9536	0.7875	0.8153
Nantou Christian Hospital	0.8715	0.8170	0.6406
Yumin Hospital	0.9593	0.9441	0.9024
Yunlin Christian Hospital	0.8352	0.8500	0.6217

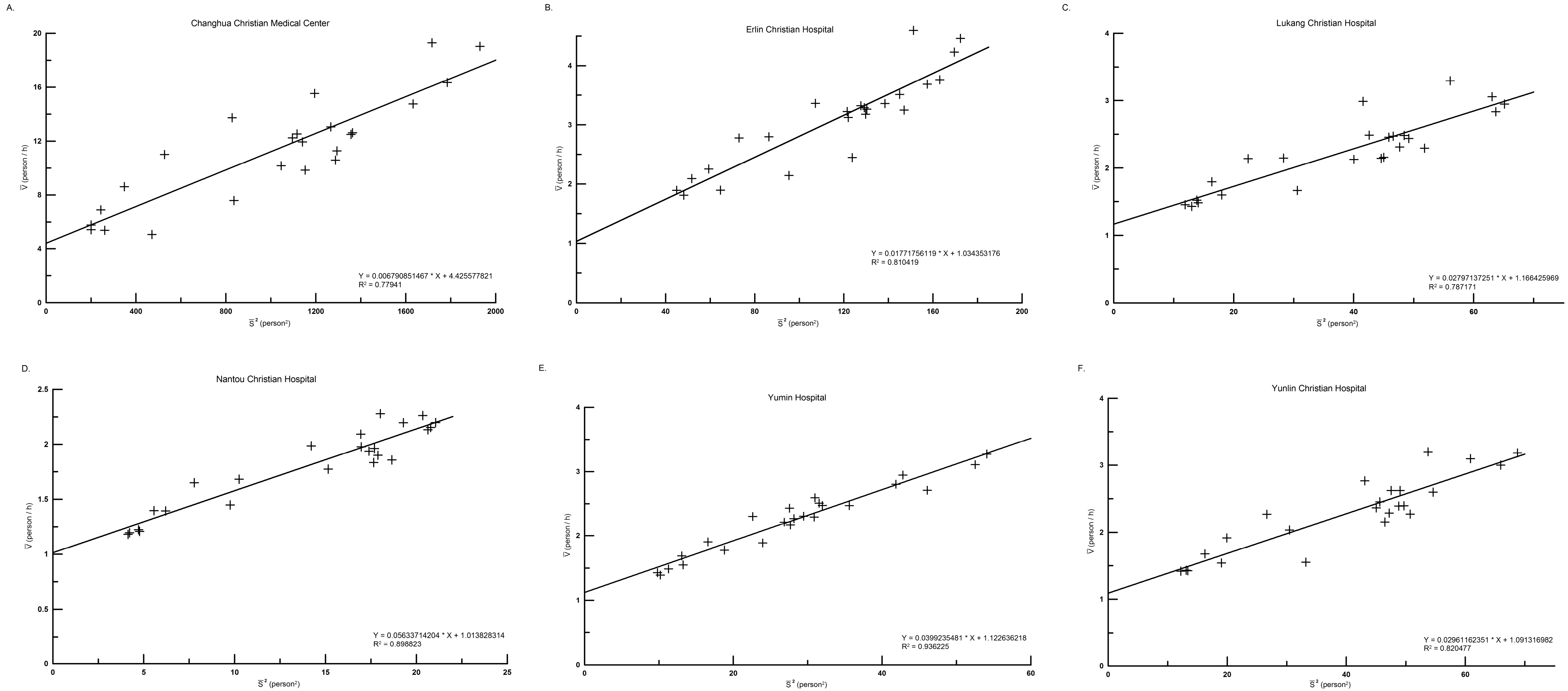
All R^2 are obtained from the linear regression lines of the mentioned plots using a truncated time period of 6-22.

ED, emergency department; R^2, the coefficient of determination

eTable 2. The values of PW for the six emergency departments in 2011 to 2013

ED-related Hospital	PW		
	2011	**2012**	**2013**
Changhua Christian Medical Center	0.0078	0.0081	0.0081
Erlin Christian Hospital	0.0150	0.0251	0.0192
Lukang Christian Hospital	0.0288	0.0221	0.0267
Nantou Christian Hospital	0.0605	0.0519	0.0407
Yumin Hospital	0.0266	0.0292	0.0340
Yunlin Christian Hospital	0.0356	0.0310	0.0236

ED, emergency department; PW, the Pan-Wen constant



eFigure 1. The $\overline{S}^2$-$\overline{V}$ plot analyses for the six EDs (Panel A-F) in 2010 with a full time period of 0-23. The linear regression lines and R^2 are depicted in the plots.