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Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints

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Abstract

Objectives: Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist.

Methods: Based on the data from 77 county-level public general hospitals (CPGHs) in Shanxi Province, China, from 2013-2018, we applied the meta-frontier and SBM-undesirable DEA model to measure the CPGHs' medical service efficiency with or without medical quality constraints and evaluate the effects of the new medical reform to explore the utilization of health resources and look for ways to improve the CPGHs' medical service efficiency.

Results： The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54).

Conclusion: To improve CPGHs' medical service efficiency, the government should increase investment in the northern region, and hospitals should improve the management level and allocate human resources rationally.

Keywords: County-level Hospital Efficiency, Medical quality, Meta-frontier DEA Model, SBM-Undesirable DEA Model.

Strengths and limitations of this study

Firstly, we applied the Meta-frontier and SBM-undesirable DEA models to evaluate the medical service efficiency, which effectively solved the problem that the efficiency score of hospitals were not on the same production frontier. Secondly, medical quality index was set as an output indicators in this study, which means that the hospitals should not only focus on the number of patients, but also focus on the medical quality. Thirdly, only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.

Background

In March 2009, the Chinese government started a new medical reform. Since the implementation of the medical reform, China has made great achievements in expanding medical security services [1,2]. The government has vigorously developed primary medical and health services and strived to improve the fairness of the health service distribution [3]. However, the distribution of health resources in China is still unreasonable, and health resources are scarce [4]. High-quality medical resources are mainly concentrated in cities, leading to a significant medical quality gap between urban and rural hospitals [5-7]. Additionally, patients prefer to choose urban hospitals, which leads to the idleness of rural hospital resources [8]. Health resource waste and shortage issues have seriously restricted the service ability of medical and health institutions and led to low medical efficiency [9]. To solve these problems and improve the quality of medical services, the government has implemented a series of reforms in rural hospitals [1,10]. China's urban and rural medical system is mainly composed of urban tertiary hospitals, urban community hospitals, county-level hospitals and township health centers [11]. Among them, county-level public general hospitals (CPGHs) act as a link in China's urban and rural medical system, and they are the leaders of rural health institutions [12 13 14]. Their medical services have a wide range of radiation and cover a large population [9]. However, county-level hospitals also have problems such as shortages of human resources, low levels of medical services and uneven distributions of resources [14-16]. For example, Wu noted that the quality of human resources in primary hospitals is not high and the medical service level is poor [17]. Jay found that the average resource levels of county-level hospitals in western

China were lower than those in other regions [18]. Therefore, it is very important to improve the utilization rate of primary health resources and the medical efficiency of county-level hospitals.

In recent years, many scholars have studied the medical efficiency of CPGHs in China. Li measured the medical efficiency of 12 CPGHs in Anhui Province and found that it has declined year by year; additionally, the medical reform effect of CPGHs was not significant [19]. Wang analyzed the medical efficiency of 127 CPGHs in China and found that the efficiency of CPGHs still has considerable room for improvement [20]. Jiang conducted a study of 1105 CPGHs in China and noted that although medical reform has increased the scale of hospitals, it has not improved the medical efficiency of CPGHs [9]. Other scholars' studies have also shown that the medical efficiency of CPGHs has room for improvement [12,21,22].

In a review of the previous literature on the medical efficiency of CPGHs, we found the following defects. 1. In China, county-level hospitals are divided into CPGHs, traditional Chinese medical hospitals, and maternal and child health care hospitals. Many studies do not subdivide the hospitals by type. Bates [23] found that different types of hospitals have different resource allocation and output structures. 2. Most studies have not considered the differences in production frontiers due to the different natural, social and economic environments in different regions. Therefore, if the DEA method is used to measure the medical efficiency of hospitals located in different regions, it will not be able to capture the technical heterogeneities among them, and the efficiency scores of the hospitals may not be accurate. 3. Ignoring the constraints of medical quality, which is an unexpected output of DEA, will seriously affect hospital efficiency. However, many studies have not considered the issue of unexpected output. Based on these defects, this study makes the following improvements: 1. the medical efficiency of 77 CPGHs, not including other types of county-level hospitals, is evaluated; 2. the meta-frontier DEA model is used to evaluate the medical efficiency of CPGHs in different regions and solve the problem of technical heterogeneity; and 3. "adverse events" are selected as a medical quality indicator. Finally, the SBM-undesirable DEA model is used to solve the problems related to unexpected outputs categorized as "adverse events".

Methods

Data Sources

The data are mainly from the 2013-2019 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected. The data excluded other types of hospitals, such as traditional Chinese medical hospitals, maternal and child health care hospitals and other medical institutions, so they met the homogeneity requirement of the DEA method.

Meta-frontier and Group Frontier DEA Models

The meta-frontier DEA model was first proposed by Battese [24]. The meta-frontier refers to the potential technical level of all decision making units (DMUs), and the group frontier refers to the actual technical level of each DMU. The difference between them is the different technology sets to which they refer.

According to the meta-frontier DEA model of Battese [25], we took the unexpected output into account. In this case, the technology set (T^{meta}) includes all technically feasible input-output combinations:

□□ = {(□ □)□ □ □ □ □ □ 0; (□)} (1)

In the above formulation, x is the input vector, y is the expected output vector, and b is the unexpected output vector. That is, to obtain a certain output $P^{meta}(y, b)$, the input (x) must be satisfied under the given technological condition (T^{meta}). The production possibility set (meta-frontier) is as follows:

$$P^{meta}(x) = \{(y, b): (x, y, b) \in T^{meta}\}$$

(2)

Therefore, the technical efficiency function of the meta-frontier from the perspective of the output can be expressed as follows:

$$TE^{meta}(x, y, b) = inf_{□} \{ >0: □ \in P^{meta}(y, b) \}$$

(3)

$\overrightarrow{□}_0$ = (□□□,□□;□□□ □□) = □□ □□ + □□□,□□□ □□) "□ □ (4)

where □ = (□□□ □□) is the direction vector, β is the maximum possible expansion degree of a desirable output along the direction vector □□, and the maximum possible reduction degree of an undesirable output along the direction vector is □ □.

According to the different levels of economic development, Shanxi Province is divided into three groups: Northern Shanxi, Central Shanxi and Southern Shanxi *(h=1, 2, 3)*. The group technology set is:

□□ = {(□□,□□,□□): □□ □ 0, □□ □ 0, □□ □ 0; □□%□□□,□□□ = 1,2,3 (4)

The production set is as follows:

$$P^h(x) = \{(y,b):(x,y,b) \in T^h\} \quad h = 1,2,3 \tag{5}$$

The group technical efficiency *(h=1,2,3)* can be expressed as:

$$D^h(x,y,b) = \sup\{\theta > 0:(x, y/\theta, b/\theta) \in P^h(x)\} \quad h = 1,2,3 \tag{6}$$

Meta-frontier technology is the envelope curve of the group frontier technology. So: $T^m = \{T^1 \cup T^2 \cup T^3\}$.

Technology Gap Ratio (TGR)

The technology gap ratio [24] can be expressed by the meta-frontier and group technology efficiency functions:

$$TGR^h(x,y,b) = \frac{D^m}{D^h(x,y,b)} \quad h = 1,2,3 \tag{7}$$

If the TGR is less than 1 or there are obvious differences between the mean values of D^m and D^h, it is necessary to divide the CPGHs into different groups. In contrast, if the TGR is close to 1 or there are no obvious differences between the mean values of D^m and D^h, there is no need to divide the CPGHs into different groups.

SBM-undesirable DEA Model

The SBM-undesirable DEA model [26] of unexpected output is used to construct the efficiency measurement model under the meta-frontier and group frontier conditions, and the formula is:

$$\rho^* = min \frac{1 - \frac{1}{m}\sum_{h=1}^{m}\frac{s_h^-}{x_{h_0}}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^y}{y_{r_0}} + \sum_{r=1}^{s_2}\frac{s_r^b}{b_{r_0}}\right)} \tag{8}$$

$$s.t. \quad x_0 = X\lambda + s^-$$

$$y_0 = Y\lambda + s^y$$

$$_0 = 4\ 2+$$

$$0, \quad 0, \quad 0$$

In the above formulation, *X*, *Y* and *B* represent the input and output vectors of different CPGHs each year. The meta-frontier represents 77 county regions, and the group frontier represents different groups in the 77 county regions; s^-, s^y and s^b are slack variables related to the input, expected output and unexpected output, respectively; *r* represents the *r*-th DMU; and r^0 represents the DMU to be assessed. The objective function decreases with 5, 5 and 5, where 0 < ≤1.

Because the data are from multiple years, homogeneity for each CPGH and statistical relations should be considered. Therefore, we adopted the global reference model proposed by Pastor and Lovell [27] to calculate the Malmquist index. This model can solve the comparability problem caused by considering different frontiers in efficiency evaluation.

Disease Complexity Adjustment for Discharged Patients

Since the disease complexity varies from hospital to hospital, it is unfair to simply input the approximate number of discharged patients into the input-output index. For example, hospitals with high technology levels are likely to treat patients with complicated conditions, and these hospitals will take more time to treat such a patient than to treat a patient with a mild illness. Hospitals with low technology levels can supply health services to patients with mild illness or light symptoms as a result of their limited technical capacities, and patients with severe illness may prefer directly seeking health services at high-level hospitals. Thus, 1000 patients in hospital-A will all have difficult and complicated diseases, and those in hospital-B will have mild diseases. However, when performing efficiency evaluation research, if a quantity of units 1000 is input without considering the complexity of the disease, it would be unfair to hospitals with high technical levels. Thus, the RCI index was used to adjust the numbers of discharged patients according to the average length of stay and bed utilization rate. The specific adjustment methods were as follows:

067 = 89 ; (66 / 66) (9)

In the above formula, $ALoS_i$ refers to the average length of stay in the *i*-th hospital, OCC_i refers to the bed utilization rate of the *i*-th hospital, and OCC_s refers to the average bed utilization rate of all evaluated hospitals. Therefore, the average length of stay will be adjusted upward for hospitals with higher bed utilization rates than the average. The actual number of discharged patients (P) was adjusted based on the RCI of each hospital, and finally, the number of discharged patients (EP) adjusted according to the RCI index was obtained. The formula is as follows:

) = ; (067 /067) (10)

Patient and public involvement

No patient involved

Results and Analysis

Variable Selection

The variables were selected according to previous empirical research and the literature [7, 9, 12, 19-22]. Input variables usually include labor and capital [28]. In our study, the numbers of registered doctors and registered nurses were used to represent the elements of human resources as input variables. Beds and equipment valued above 10,000 yuan were used as capital elements. The total visits, the number of discharged patients (EP) adjusted by the RCI and the number of operations were used as output variables. The number of adverse events was used to replace the unexpected output variable as a quality index. The descriptive statistics of the input-output indicators are shown in Table 1.

Table 1 Descriptive statistics

Input/output	Variable	**Mean**	**Std. Dev.**	Min	Max
Input variables	doctor	95.232	42.017	18	278
	nurse	117.985	71.658	9	390
	bed	250.217	125.748	80	790
	machine	226.736	145.973	35	831
Desirable output variables	treatment	95432.120	58710.450	16351	292534
	EP	9607.892	6610.737	756.4231	32707.7
	operations	1470.729	1189.186	81	7926
Undesirable output variables	adverse events	68.712	38.462	10	200

Note: The sample size in the model was 462

Test and Analysis of the Technology Gap Ratio (TGR)

Under a quality constraint, a mean value comparison test of the obtained technology gap ratio (TGR) was performed, as shown in Table 2. Assuming that the mean value was 1 and the significance level was 95%, the results showed that the average TGR of each group was less than 1. After performing calculations, from 2013 to 2018, the mean value of the hospital TGR in the southern group was at the highest level, close to 1, reaching 0.93, followed by that of the central group of 0.91, and finally that of the northern group at only 0.63. This result indicated that the southern group was closest to the meta-frontier of technology in county-level public general hospitals, followed by the central group and the northern group. Obviously, both the overall TGR and the regional TGR values were significantly different from the assumed mean value of 1. Therefore, the heterogeneity of the division of public hospitals in Shanxi Province was very obvious, and this finding agreed the conditions of the DEA meta-frontier model; thus, the meta-frontier model could be suitably applied to analyze the results.

Table 2 Comparative test results of the mean value of the technology gap among county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

Region	Mean TGR	t	P
North	0.62649	-17.2815	0.000
Central	0.907907	-8.9249	0.000
South	0.9328708	-6.9778	0.000
Entire	0.8494894	-15.6809	0.000

After calculating the efficiency of county-level general hospitals in Shanxi Province under meta-frontier and group frontier conditions, the temporal trends of the technology gaps in the north, central and southern regions under the quality constraint were further compared. The results are shown in Figure 1.

Figure 1 shows that the mean value of the TGR in the southern and central regions of Shanxi Province was high, while that in the northern region was the lowest, indicating that the central and southern regions provide better hospital management and medical levels as a whole than did the norther region; additionally, they are closer to the technological frontier. The mean value of the TGR in the central and southern regions fluctuated at a high level and remained in a basically stable state, but the mean value of the TGR in the northern region considerably changed. Except for a slight increase in the mean TGR in 2016, other years experienced a downward trend, which indicated that the medical level in the northern region decreased and that different frontiers influenced the efficiency of county-level public general hospitals in different regions of Shanxi Province.

Time Series Analysis of the Technical Efficiency of Hospitals

Figures 2A and B show the trend of the average comprehensive efficiency of sample hospitals in Shanxi Province and in three major regions from 2013-2018 under the meta-frontier and group frontier, respectively. Taking the meta-frontier in Figure 2A as a reference, the overall average medical service efficiency of county-level public general hospitals was more than 0.6, and the medical service efficiency in each region was relatively stable in each year; notably, the efficiency in the northern region displayed a slow downward trend. Referring to Figure 2B, the overall average efficiency for the group frontier was approximately 0.75, the southern region was relatively stable, and the trends in the northern and central regions involved inverted U-shaped curves in the early stage; however, all the regions experienced a significant increase in 2018.

Figures 2C and D show the trend of the average comprehensive efficiency of the sample hospitals in Shanxi Province and in three major regions under the meta-frontier and the group frontier conditions, respectively, based on the quality constraints from 2013 to 2018. Taking the common frontier in Figure 2C as a reference, the overall average medical service efficiency of county-level public general hospitals was approximately 0.63, and the medical service efficiency trend in various regions displayed an inverted U-shaped curve in each year; that is, it fluctuated and rose from 2013 to 2016 and then dropped rapidly after 2016. With reference to Figure 2D, the overall average efficiency under the group frontier was approximately 0.75, and the medical service efficiency trend in the northern region displayed a U-shaped curve that fluctuated and decreased from 2013 to 2016 and then rose slowly after 2016. Moreover, the efficiency trends in the central and southern regions were the same as those for the meta-frontier.

Analysis of the Differences in Hospital Technical Efficiency

The distribution of the service efficiency of public general hospitals in Shanxi Province is shown in Figure 3. Graph A shows the distribution of hospital efficiency without quality constraints, and graph B presents the distribution of hospital efficiency under quality constraints. In terms of location, the peak position of the distribution curve in Figure 3B moves to the right compared with that in Figure 3A, indicating an overall efficiency improvement. The kurtosis of the distribution curve for the central and southern regions in Figure 3B is greater than that in Figure 3A, indicating that the

distribution of the efficiency was more concentrated in B. The northern distribution curve in Figure 3B displays an obvious bimodal state, indicating that the efficiency distribution was somewhat scattered. Therefore, quality constraints were very important in the hospital efficiency evaluation. A lack of quality constraints would lead to certain deviations in the evaluation results, and the results would not comprehensively reflect the actual operation status of the medical system.

An analysis of the hospital efficiency distribution in Figure 3B was performed. First, for the location, the distribution curves of the hospital efficiency density in the northern, southern and central regions sequentially moved to the right. The distribution curves of the southern and central regions were closely interlaced, indicating that the hospital efficiency levels in the southern and central regions are similar and significantly higher than the level in the northern region.

Second, the distribution curve of the efficiency density in northern hospitals peaks, and the distribution curves of the efficiency density for the central and southern hospitals displays broad kurtosis.

Finally, in terms of shape, the distribution curve of the efficiency density for northern hospitals is bimodal, and those for the central and southern hospitals are unimodal, suggesting that most hospitals in the central and southern regions have little difference in medical level, while the medical level of northern hospitals is polarized; this relation reflect the concept of "the strong get stronger, and the weak get weaker" (Matthew's effect).

Analysis of the Changes in Hospital Technical Efficiency Rankings

To show the changes in efficiency among the sample hospitals before and after the

implementation of quality constraints, the comprehensive efficiency values of sample hospitals under the two constraint conditions were ranked, and the changes in hospital rankings were compared. The results are shown in Figure 4. In the northern region, the ranking of hospital 17 increased the fastest, and the rankings of hospitals 6 and 13 decreased most obviously. In the central region, the ranking of hospital 24 increased the fastest, and the ranking of hospital 29 decreased the most. In the southern region, the ranking of hospital 71 increased the fastest, and the ranking of hospital 67 decreased the most.

By analyzing the unexpected outputs of adverse events at hospitals, it was found that the changes in efficiency rankings were related to the unexpected outputs of adverse events; notably, the efficiency ranking increased when the unexpected output level was low, and the ranking decreased when the unexpected output level was high. For example, the average unexpected output of hospitals in the northern region was -14.35, and that of hospital 17, with a medical quality higher than that of most hospitals, was -3.38. However, the average unexpected outputs of hospitals 6 and 13 were -23.78 and -31.08, respectively, and the corresponding medical quality was lower than that of other hospitals. Additionally, the average unexpected output values of hospitals in the central and southern regions were -15.3 and -19.22, respectively, and the average unexpected output values of hospitals 24 and 71 were only -3.09 and -3.49, respectively. Moreover, the average unexpected output values of hospitals 29 and 67 were -23.99 and -57.25, respectively.

The Spearman rank correlation test was used to determine whether there was a

correlation between the hospital efficiency values under the two different constraints. The significance level was 1%. The results showed that there was a positive correlation between the efficiency values of sample hospitals under the two constraints. According to the results, the three regions were different: the southern region had the highest similarity, with a correlation coefficient of 0.9673, and the greatest difference was observed in the northern region, with a correlation coefficient of 0.8452.

Discussion

This paper used the meta-frontier model and SBM-undesirable model to calculate the efficiency of county-level public hospitals in Shanxi Province from 2013 to 2018. Then, we evaluated the reform effect and resource utilization rate of county hospitals and explored the influence of medical quality on hospital efficiency.

The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). In other studies, the average efficiency of county hospitals in Chongqing was 0.83 [12], in Anhui Province was 0.956 [19], and in China, as a mean value, was 0.7 [20], suggesting that the efficiency of county-level hospitals in Shanxi Province is obviously low; additionally, the utilization rate of existing resources is relatively low, and the technology used in inefficient. To improve the efficiency level of county-level hospitals, in addition to increasing investments to alleviate resource shortages, it is necessary to improve the utilization efficiency of resources, such as improving hospital management, rationally allocating human resources, and optimizing capital investments [29].

The results showed that the efficiency of county-level public hospitals in Shanxi Province did not improve and even declined in some areas from 2013 to 2018 (Figure 2C). Although the reform of county-level hospitals was initiated in 2012, the effect was not remarkable, as also noted by Jiang et al. [9]. Moreover, the study found that there were regional differences in the efficiency of county-level public hospitals in Shanxi Province. The efficiency level of county-level public hospitals in the central and southern regions of Shanxi Province was high, while the efficiency level in the northern region was comparatively low (Figure 2A and Figure 2C); these trends were also reflected by the technology gap ratio distribution in each region (Figure 1), which indicated that the county-level hospitals in the northern region were far from the technological frontier. Therefore, increasing the resource inputs for hospitals in the northern region of the province should be prioritized to improve their medical levels. Additionally, the population and economic level in northern Shanxi Province are lower than those in the central and southern regions [30]; thus, hospital efficiency may be related to the economic environment and population.

This study also showed that quality constraints had an important impact on hospital efficiency evaluation (Figures 3 and 4). Neglecting medical quality output could lead to underestimates of the hospital efficiency level. This finding could potentially be attributed to the fact that medical quality is often related to hospital management and human resources [31]. With improvements in hospital management and medical treatment ability, medical quality will also increase, as will the corresponding hospital efficiency. Improving the quality of medical services is often the goal of public hospitals [32], but many hospitals begin to expand blindly, resulting in inefficiency [9,20,33]. Pang [34] et al. noted that improperly scaled expansion can lead to technical efficiency in the short term but not in the long term. Therefore, to improve the medical quality level, increasing the technological capacity and improving management are steps.

Conclusion

This showed that after the implementation of county-level public hospital reform, the efficiency level of county-level public hospitals in Shanxi Province did not improve but remained low. Notably, the utilization rate of resources was low, and the reform effect was not obvious. There are differences in the efficiency of county-level hospitals in different regions, with the highest efficiency in the central region, the second-highest level in the southern region and the lowest level in the northern region. To improve the efficiency of hospitals, support to the northern region should be strengthened, hospital management should be improved, and health human resources should be rationally allocated.

The results also indicated that quality factors have a significant impact on hospital efficiency evaluation. The keys to improving the level of medical quality are to improve the proportion of technical personnel and the level of hospital management. The expansion of county-level hospitals should consider the economic level and service area in the region to avoid expansion and blind investment, potentially resulting in wasted resources.

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Authors' contribution

All authors made significant contribution to this study. JL conceptualized the study. WL collected and analyzed the data. BBG wrote the first draft of the manuscript. JL and WL interpreted the results and revised the manuscript. The final version submitted for publication was read and approved by authors.

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Availability of data and materials

The data sets analyzed during this study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

Not Applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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figure legend/caption

Figure 1 shows that the mean value of the TGR in the southern and central regions of Shanxi Province was high, while that in the northern region was the lowest, indicating that the central and southern regions provide better hospital management and medical levels as a whole than did the norther region; additionally, they are closer to the technological frontier.

Figures 2A and B show the trend of the average comprehensive efficiency of sample hospitals in Shanxi Province and in three major regions from 2013-2018 under the meta-frontier and group frontier, respectively.

The distribution of the service efficiency of public general hospitals in Shanxi Province is shown in Figure 3. Graph A shows the distribution of hospital efficiency without quality constraints, and graph B presents the distribution of hospital efficiency under quality constraints.

The results are shown in Figure 4. To show the changes in efficiency among the sample hospitals before and after the implementation of quality constraints, the comprehensive efficiency values of sample hospitals under the two constraint conditions were ranked, and the changes in hospital rankings were compared.

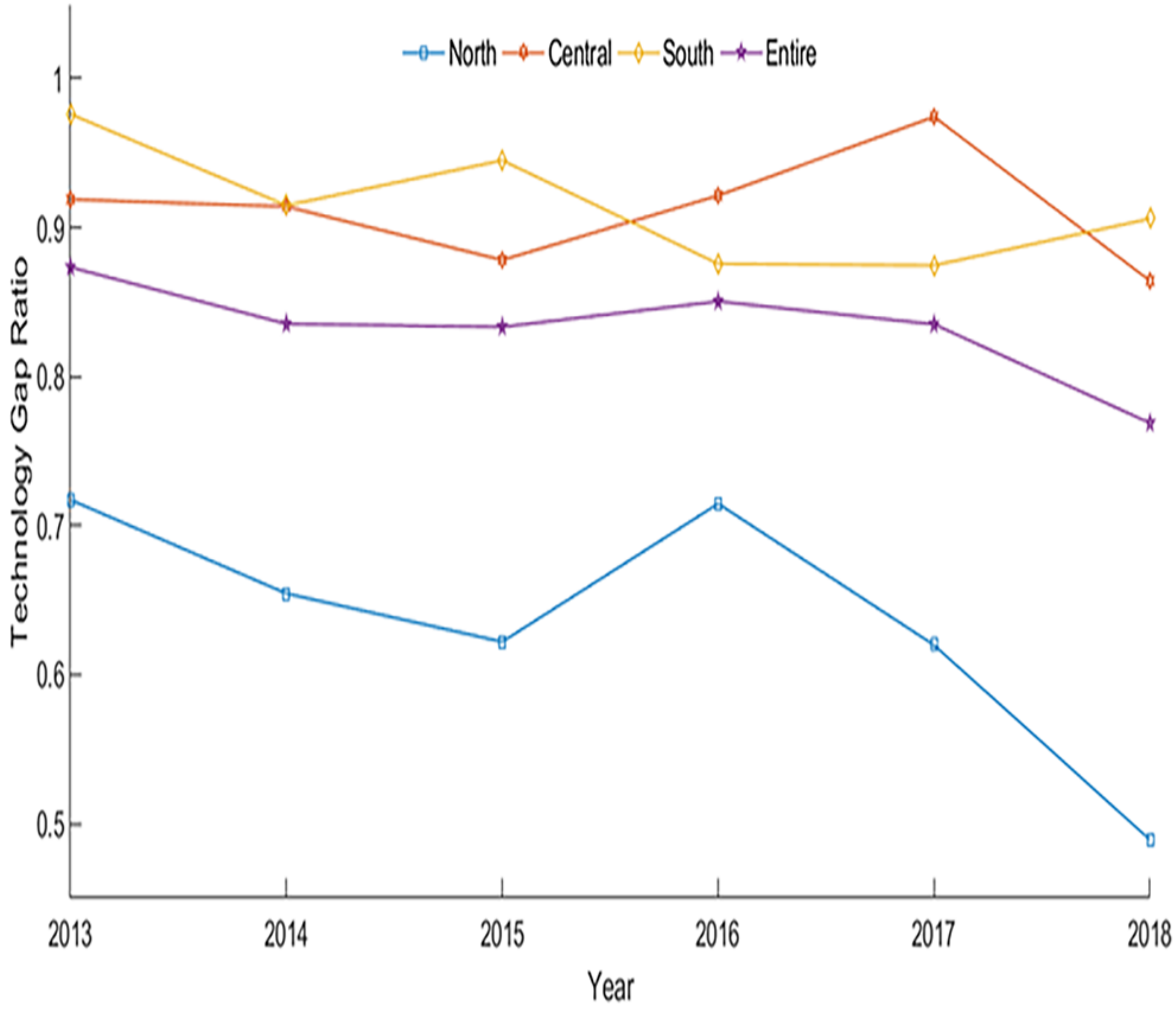

Fig.1 The technology gap ratios in northern, central and southern Shanxi Province from 2013 to 2018 under the quality constraint

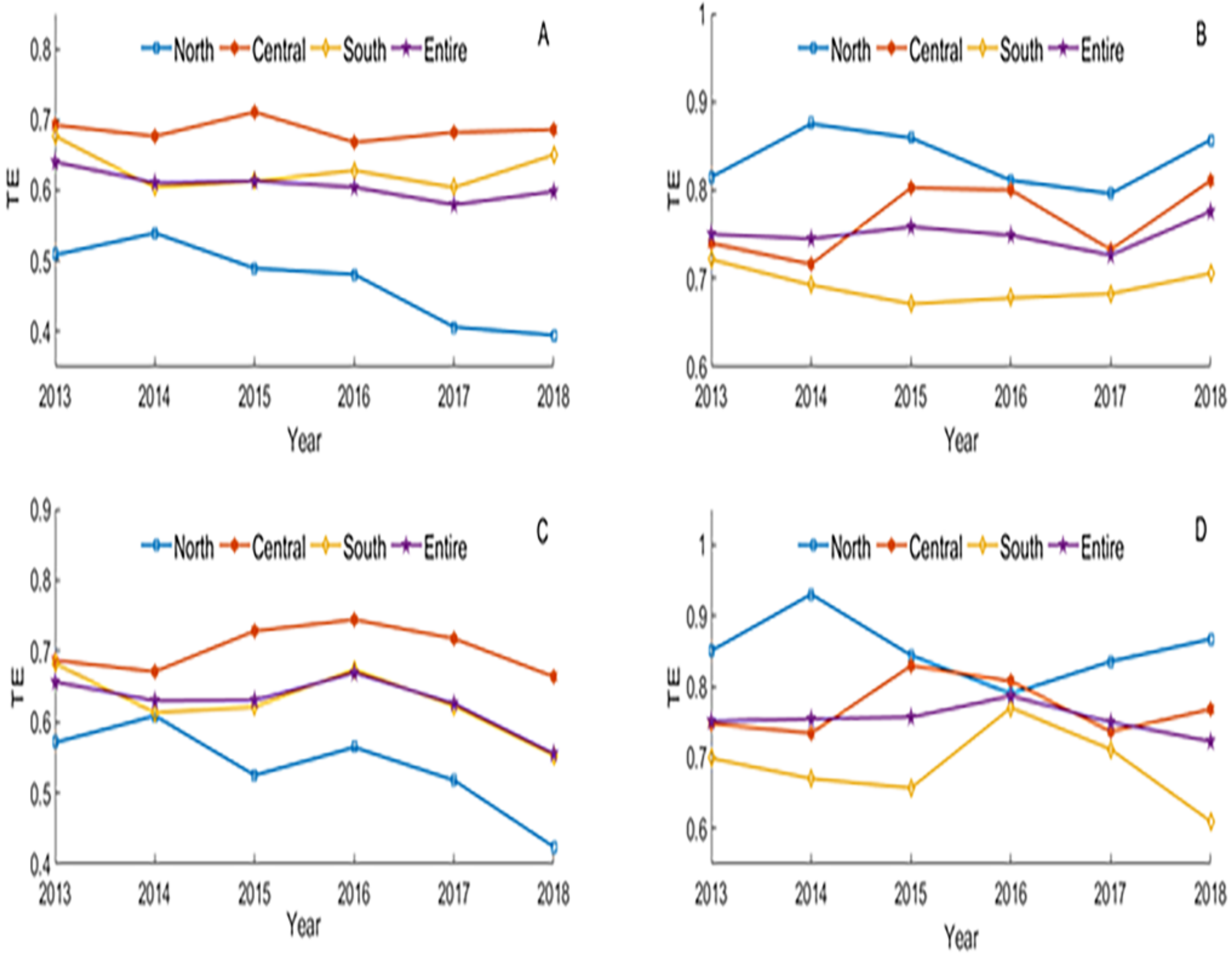

Fig.2 Efficiency changes of county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

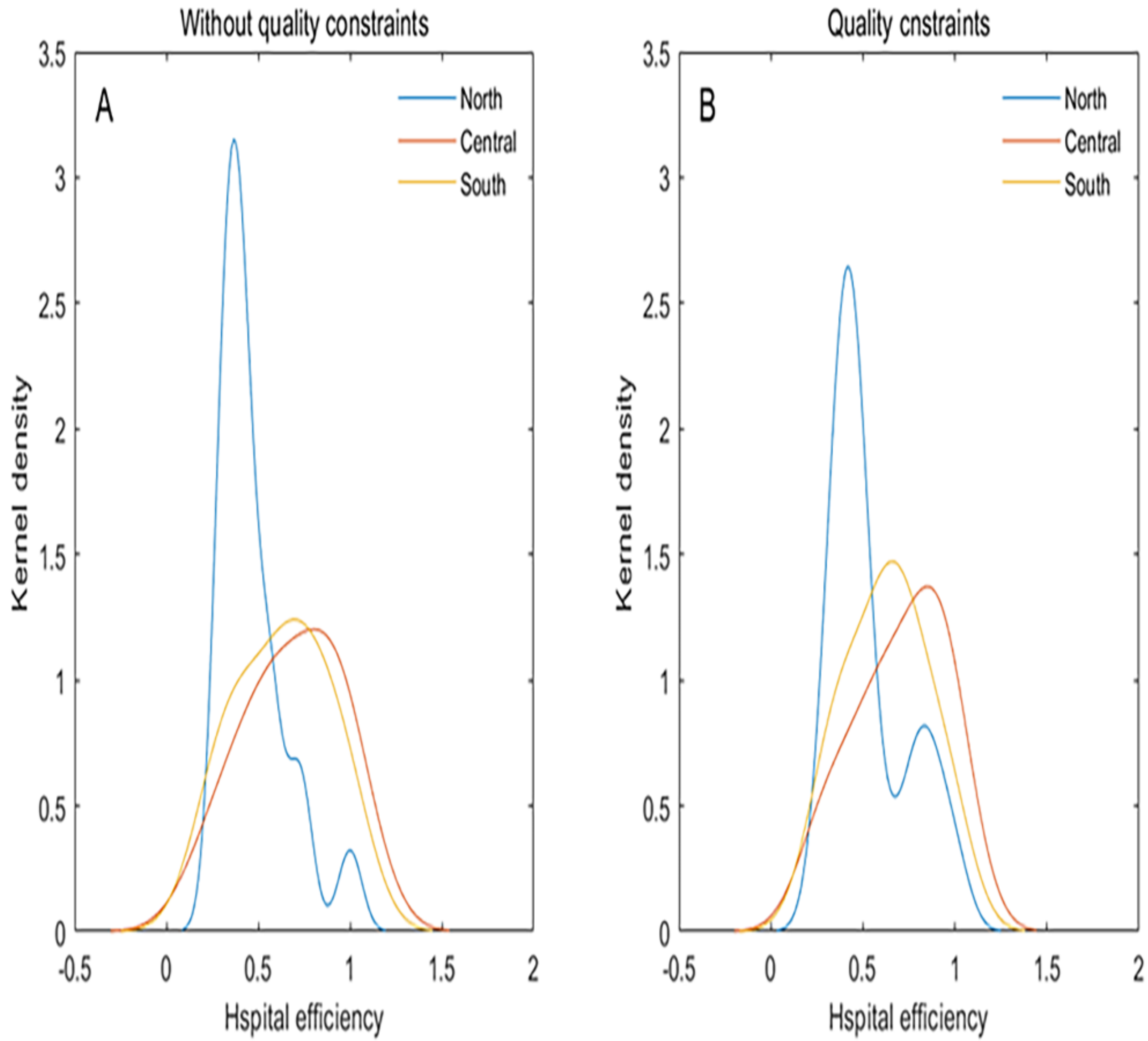

Fig.3 Distribution of the service efficiency of county-level public general hospitals in Shanxi Province

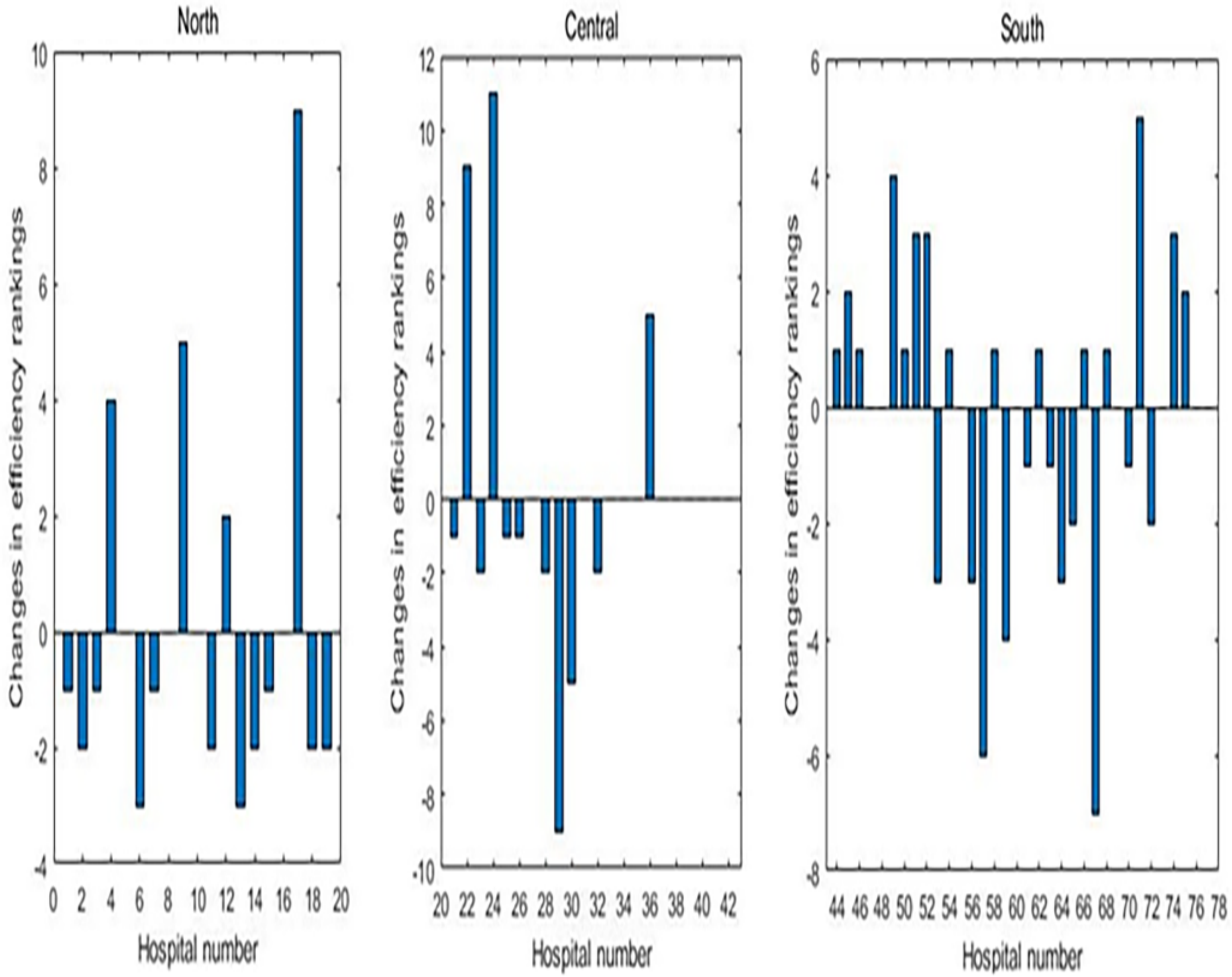

Fig.4 Changes in the efficiency rankings of county-level public general hospitals in Shanxi Province before and after the implementation of quality constraints

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Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints

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Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints

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Abstract

Objectives: Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist.

Methods: Based on the data from 77 county-level public general hospitals (CPGHs) in Shanxi Province, China, from 2013-2018, we applied the meta-frontier and SBM-undesirable DEA model to measure the CPGHs' medical service efficiency with or without medical quality constraints and evaluate the effects of the new medical reform to explore the utilization of health resources and look for ways to improve the CPGHs' medical service efficiency.

Results: The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54).

Conclusion: To improve CPGHs' medical service efficiency, the government should increase investment in the northern region, and hospitals should improve the management level and allocate human resources rationally.

Keywords: County-level Hospital Efficiency, Medical quality, Meta-frontier DEA Model, SBM-Undesirable DEA Model.

Strengths and limitations of this study

- We applied the Meta-frontier and SBM-undesirable DEA models to evaluate the medical service efficiency, which effectively solved the problem that the efficiency score of hospitals were not on the same production frontier.
- Medical quality index was set as an output indicators in this study, which means that the hospitals should not only focus on the number of patients, but also focus on the medical quality.
- Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.

Background

In March 2009, the Chinese government started a new medical reform. Since the implementation of the medical reform, China has made great achievements in expanding medical security services [1,2]. The government has vigorously developed primary medical and health services and strived to improve the fairness of the health service distribution [3]. However, the distribution of health resources in China is still unreasonable, and health resources are scarce [4]. High-quality medical resources are mainly concentrated in cities, leading to a significant medical quality gap between urban and rural hospitals [5-7]. Additionally, patients prefer to choose urban hospitals, which leads to the idleness of rural hospital resources [8]. Health resource waste and shortage issues have seriously restricted the service ability of medical and health institutions and led to low medical efficiency [9]. To solve these problems and improve the quality of medical services, the government has implemented a series of reforms in rural hospitals [1,10]. China's urban and rural medical system is mainly composed of urban tertiary hospitals, urban community hospitals, county-level hospitals and township health centers [11]. Among them, county-level public general hospitals (CPGHs) act as a link in China's urban and rural medical system, and they are the leaders of rural health institutions [12-14]. Their medical services have a wide range of radiation and cover a large population [9]. However, county-level hospitals also have problems such as shortages of human resources, low levels of medical services and uneven distributions of resources [14-16]. For example, Wu noted that the quality of human resources in primary hospitals is not high and the medical service level is poor

[17]. Jay found that the average resource levels of county-level hospitals in western China were lower than those in other regions [18]. Therefore, it is very important to improve the utilization rate of primary health resources and the medical efficiency of county-level hospitals.

In recent years, many scholars have studied the medical efficiency of CPGHs in China. Li measured the medical efficiency of 12 CPGHs in Anhui Province and found that it has declined year by year; additionally, the medical reform effect of CPGHs was not significant [19]. Wang analyzed the medical efficiency of 127 CPGHs in China and found that the efficiency of CPGHs still has considerable room for improvement [20]. Jiang conducted a study of 1105 CPGHs in China and noted that although medical reform has increased the scale of hospitals, it has not improved the medical efficiency of CPGHs [9]. Other scholars' studies have also shown that the medical efficiency of CPGHs has room for improvement [12,21,22]. Super SBM-undesirable DEA model was used by (A. Monzeli) to measure the hospitals' emergency departments, which indicated that the undesirable output can determine the hospitals' efficiency[23].

In a review of the previous literature on the medical efficiency of CPGHs, we found the following defects. 1. In China, county-level hospitals are divided into CPGHs, traditional Chinese medical hospitals, and maternal and child health care hospitals. Many studies do not subdivide the hospitals by type. Bates [24] found that different types of hospitals have different resource allocation and output structures. 2. Most studies have not considered the differences in production frontiers due to the different natural, social and economic environments in different regions. However, in other industries, some relevant scholars have added relevant non-expected output indicators for research when evaluating efficiency. In 2012, Majid Azadi [25] used SBM-Undesirable DEA model to evaluate the efficiency of suppliers with adverse events, No. Of personnel and Average time for serving customers (HR) were selected as input indicators and Profit margin as expected output. No. Of Dissatisfied customers were considered as Undesirable outputs, and the results showed that the SBM-Undesirable DEA model could help decision makers choose suitable suppliers. In 2021, Tong Guang Ji [26] evaluated agro-ecological efficiency in 136 developing countries using SBM-Undesirable DEA model, Input indicators include Freshwater consumption, Agricultural land area, Fertilizer consumption and Labor; expected output indicators include Production and Forest area. Non-expected output indicators were selected as Methane emissions and Nitrous oxide emissions. The results show that choosing effective marginal tradeoff does not reduce the relative efficiency of dMU below the effective boundary line. Thus, this approach enables decision makers to determine the optimal marginal tradeoff point for optimal efficiency and to determine which output factors require specialized brainstorming to design effective policies. Therefore, if the DEA(Data Envelopment Analysiaas) method is used to measure the medical efficiency of hospitals located in different regions, it will not be able to capture the technical heterogeneities among them, and the efficiency scores of the hospitals may not be accurate. 3. Ignoring the constraints of medical quality, which is an unexpected output of DEA(Data Envelopment Analysis), will seriously affect hospital efficiency. However, many studies have not considered the issue of unexpected output. Based on these defects, this study makes the following improvements: 1. the medical efficiency of 77 CPGHs, not including other types of county-level hospitals, is evaluated; 2. the meta-frontier DEA(Data Envelopment Analysis) model is used to evaluate the medical efficiency of CPGHs in different regions and solve the problem of technical heterogeneity; and 3. "adverse events" are selected as a medical quality indicator. Finally, the SBM-undesirable DEA model is used to solve the problems related to unexpected outputs categorized as "adverse events".

Methods

Data Sources

The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected[27]. The data excluded other types of hospitals, such as traditional Chinese medical hospitals, maternal and child health care hospitals and other medical institutions, so they met the homogeneity requirement of the DEA(Data Envelopment Analysis) method.

Meta-frontier and Group Frontier DEA Models

The meta-frontier DEA(Data Envelopment Analysis) model was first proposed by Battese [28]. The meta-frontier refers to the potential technical level of all decision making units (DMUs), and the group frontier refers to the actual technical level of each DMU. The difference between them is the different technology sets to which they refer.

According to the meta-frontier DEA(Data Envelopment Analysis) model of Battese [29], we took the unexpected output into account. In this case, the technology set (T^{meta}) includes all technically feasible input-output combinations:

$$T^{meta} = \left\{ \begin{matrix} (x,y,b):x \geq 0, y \geq 0, b \geq 0; \\ x\ can\ produce\ \ (y,b) \end{matrix} \right\} \quad (1)$$

In the above formulation, *x* is the input vector, *y* is the expected output vector, and *b* is the unexpected output vector. That is, to obtain a certain output P^{meta} *(y, b)*, the input *(x)* must be satisfied under the given technological condition *(T^{meta})*. The production possibility set (meta-frontier) is as follows:

$$P^{meta}(x) = \{(y,b) : (x,y,b) \in T^{meta}\} \quad (2)$$

Therefore, the technical efficiency function of the meta-frontier from the perspective of the output can be expressed as follows:

$$TE^{meta}(x,y,b) = inf_{\beta}\{\beta > 0 : (y/\beta) \in P^{meta}(y,b)\} \quad (3)$$

According to the different levels of economic development, Shanxi Province is divided into three groups: Northern Shanxi, Central Shanxi and Southern Shanxi *(h=1, 2, 3)*. The group technology set is:

$$T^{h} = \{(x_h,y_h,b_h):x_h \geq 0, y_h \geq 0, b_h \geq 0; x_h \to (y_h,b_h)\}, h = 1,2,3 \quad (4)$$

The production set is as follows:

$$P^{h}(x_h) = \{(y_h,b_h):(x_h,y_h,b_h) \in T^{h}\}, h = 1,2,3 \quad (5)$$

The group technical efficiency *(h=1,2,3)* can be expressed as:

$$TE^{h}(x_h,y_h,b_h) = inf_{\beta}\{\beta > 0:(y_h/\beta) \in P^{h}(y_h,b_h)\}, h = 1,2,3 \quad (6)$$

Meta-frontier technology is the envelope curve of the group frontier technology. So:$T^{m} = \{T^{1} \cup T^{2} \cup T^{3}\}$.

Technology Gap Ratio (TGR)

The technology gap ratio [28] can be expressed by the meta-frontier and group technology efficiency functions(The results are shown in Figure 1.):

$$TGR^h(x_h,y_h,b_h) = \frac{TE^{meta}(x,y,b)}{TE^h(x_h,y_h,b_h)}, h = 1,2,3 \quad (7)$$

Fig 1 Schematic diagram of common frontier and group frontier

Take R Hospital located in Group3 as an example, then

$$TE^{meta}(R) = \frac{OC}{OA}; TE^h(R) = \frac{OC}{OB}; TGR^h(R) = \frac{TE^{meta}}{TE^h} = \frac{OC/OA}{OC/OB} = \frac{OB}{OA} \quad (8)$$

If the TGR is less than 1 or there are obvious differences between the mean values of TE^{meta} and TE^h, it is necessary to divide the CPGHs into different groups. In contrast, if the TGR is close to 1 or there are no obvious differences between the mean values of TE^{meta} and TE^h, there is no need to divide the CPGHs into different groups.

SBM-undesirable DEA Model

The SBM-undesirable（Slacks-based Measurement-undesirable） DEA model [30] of unexpected output is used to construct the efficiency measurement model under the meta-frontier and group frontier conditions, and the formula is:

$$\rho^* = min\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{S_{i0}^{-}}{x_{i0}}}{1+\frac{1}{S}\left(\sum_{r=1}^{S_1}\frac{S_r^g}{y_{r0}^g}+\sum_{r=1}^{S_2}\frac{S_r^b}{y_{r0}^b}\right)}$$

Subject to

$x_0 = X\lambda + S^-$

$y_0^g = Y\lambda - S^g$

$y_0^b = Y\lambda + S^b$

$L \leq e\lambda \leq U$

$S^-, S^g, S^b, \lambda \geq 0. \quad (9)$

In the above formulation, X, Y and B represent the input and output vectors of different CPGHs each year. The meta-frontier represents 77 county regions, and the group frontier represents different groups in the 77 county regions; s^-, s^y and s^b are slack variables related to the input, expected output and unexpected output, respectively; r represents the r-th DMU; and r^0 represents the DMU to be assessed. The objective function ρ^* decreases with $s_h^-(\forall h)$, $s_r^y(\forall r)$ and $s_r^b(\forall r)$, where $0 < \rho^* \leq 1$.

Because the data are from multiple years, homogeneity for each CPGH and statistical relations should be considered. Therefore, we adopted the global reference model proposed by Pastor and Lovell [31] to calculate the Malmquist index. This model can solve the comparability problem caused by considering different frontiers in efficiency evaluation.

Disease Complexity Adjustment for Discharged Patients

Since the disease complexity varies from hospital to hospital, it is unfair to simply input the approximate number of discharged patients into the input-output index. For example, hospitals with high technology levels are likely to treat patients with complicated conditions, and these hospitals will take more time to treat such a patient than to treat a patient with a mild illness. Hospitals with low technology levels can supply health services to patients with mild illness or light symptoms as a result of their limited technical capacities, and patients with severe illness may prefer directly seeking health services at high-level hospitals. Thus, 1000 patients in hospital-A will all have difficult and complicated diseases, and those in hospital-B will have mild diseases. However, when performing efficiency evaluation research, if a quantity of units 1000 is input without considering the complexity of the disease, it would be unfair to hospitals with high technical levels. However, the RCI index can be used to adjust the numbers of discharged patients according to the average length of stay and bed utilization rate[32]. Since the poor quality of the patient records in county-level hospitals, we select RCI index, which provides a reference for efficiency evaluation in underdeveloped areas. The specific adjustment methods were as follows:

$$RCI_i = ALoS_i * (OCC_i/OCC_s) \quad (10)$$

In the above formula, $ALoS_i$ refers to the average length of stay in the *i*-th hospital, OCC_i refers to the bed utilization rate of the *i*-th hospital, and OCC_s refers to the average bed utilization rate of all evaluated hospitals. Therefore, the average length of stay will be adjusted upward for hospitals with higher bed utilization rates than the average. The actual number of discharged patients (P) was adjusted based on the RCI of each hospital, and finally, the number of discharged patients (EP) adjusted according to the RCI index was obtained. The formula is as follows:

$$EP = P * (RCI_i/RCI_s) \quad (11)$$

Patient and public involvement

No patient involved

Results and Analysis

Variable Selection

The variables were selected according to previous empirical research and the literature [7, 9, 12, 19-22]. Input variables usually include labor and capital [33]. In our study, the numbers of registered doctors and registered nurses were used to represent the elements of human resources as input variables. Beds and equipment valued above

10,000 yuan were used as capital elements. The total visits, the number of discharged patients (EP) adjusted by the RCI and the number of operations were used as output variables. The number of adverse events was used to replace the unexpected output variable as a quality index[34]. The descriptive statistics of the input-output indicators are shown in Table 1.

Table 1 Descriptive statistics

Input/output	Variable	**Mean**	**Std. Dev.**	Min	Max
Input variables	doctor	95.232	42.017	18	278
	nurse	117.985	71.658	9	390
	bed	250.217	125.748	80	790
	machine	226.736	145.973	35	831
Desirable output variables	treatment	95432.120	58710.450	16351	292534
	EP	9607.892	6610.737	756.4231	32707.7
	operations	1470.729	1189.186	81	7926
Undesirable output variables	adverse events	68.712	38.462	10	200

Note: The sample size in the model was 462

Test and Analysis of the Technology Gap Ratio (TGR)

Under a quality constraint, a mean value comparison test of the obtained technology gap ratio (TGR) was performed, as shown in Table 2. Assuming that the mean value was 1 and the significance level was 95%, the results showed that the average TGR of each group was less than 1. After performing calculations, from 2013 to 2018, the mean value of the hospital TGR in the southern group was at the highest level, close to 1, reaching 0.93, followed by that of the central group of 0.91, and finally that of the northern group at only 0.63. This result indicated that the southern group was closest to the meta-frontier of technology in county-level public general hospitals, followed by the central group and the northern group. Obviously, both the overall TGR and the regional TGR values were significantly different from the assumed mean value of 1. Therefore, the heterogeneity of the division of public hospitals in Shanxi Province was very obvious, and this finding agreed the conditions of the DEA(Data Envelopment Analysis) meta-frontier model; thus, the meta-frontier model could be suitably applied to analyze the results.

Table 2 Comparative test results of the mean value of the technology gap among county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

Region	Mean TGR	t	P
North	0.62649	-17.2815	0.000
Central	0.907907	-8.9249	0.000
South	0.9328708	-6.9778	0.000
Entire	0.8494894	-15.6809	0.000

After calculating the efficiency of county-level general hospitals in Shanxi Province under meta-frontier and group frontier conditions, the temporal trends of the technology gaps in the north, central and southern regions under the quality constraint were further compared. The results are shown in Figure 2.

Figure 2 shows that the mean value of the TGR in the southern and central regions of Shanxi Province was high, while that in the northern region was the lowest, indicating that the central and southern regions provide better hospital management and medical levels as a whole than did the norther region; additionally, they are closer to the technological frontier. The mean value of the TGR in the central and southern regions fluctuated at a high level and remained in a basically stable state, but the mean value of the TGR in the northern region considerably changed. Except for a slight increase in the mean TGR in 2016, other years experienced a downward trend, which indicated that the medical level in the northern region decreased and that different frontiers influenced the efficiency of county-level public general hospitals in different regions of Shanxi Province.

Time Series Analysis of the Technical Efficiency of Hospitals

Figures 3A and B show the trend of the average comprehensive efficiency of sample hospitals in Shanxi Province and in three major regions from 2013-2018 under the meta-frontier and group frontier, respectively. Taking the meta-frontier in Figure 3A as a reference, the overall average medical service efficiency of county-level public general hospitals was more than 0.6, and the medical service efficiency in each region was relatively stable in each year; notably, the efficiency in the northern region displayed a slow downward trend. Referring to Figure 3B, the overall average efficiency for the group frontier was approximately 0.75, the southern region was relatively stable, and the trends in the northern and central regions involved inverted U-shaped curves in the early stage; however, all the regions experienced a significant increase in 2018.

Figures 3C and D show the trend of the average comprehensive efficiency of the sample hospitals in Shanxi Province and in three major regions under the meta-frontier and the group frontier conditions, respectively, based on the quality constraints from 2013 to 2018. Taking the common frontier in Figure 3C as a reference, the overall average medical service efficiency of county-level public general hospitals was approximately 0.63, and the medical service efficiency trend in various regions displayed an inverted U-shaped curve in each year; that is, it fluctuated and rose from 2013 to 2016 and then dropped rapidly after 2016. With reference to Figure 3D, the overall average efficiency under the group frontier was approximately 0.75, and the medical service efficiency trend in the northern region displayed a U-shaped curve that fluctuated and decreased from 2013 to 2016 and then rose slowly after 2016. Moreover, the efficiency trends in the central and southern regions were the same as those for the meta-frontier.

Analysis of the Differences in Hospital Technical Efficiency

The distribution of the service efficiency of public general hospitals in Shanxi Province is shown in Figure 4. Graph A shows the distribution of hospital efficiency without quality constraints, and graph B presents the distribution of hospital efficiency under quality constraints. In terms of location, the peak position of the distribution curve in Figure 4B moves to the right compared with that in Figure 4A, indicating an overall efficiency improvement. The kurtosis of the distribution curve for the central and southern regions in Figure 4B is greater than that in Figure 4A, indicating that the

distribution of the efficiency was more concentrated in B. The northern distribution curve in Figure 4B displays an obvious bimodal state, indicating that the efficiency distribution was somewhat scattered. Therefore, quality constraints were very important in the hospital efficiency evaluation. A lack of quality constraints would lead to certain deviations in the evaluation results, and the results would not comprehensively reflect the actual operation status of the medical system.

An analysis of the hospital efficiency distribution in Figure 4B was performed. First, for the location, the distribution curves of the hospital efficiency density in the northern, southern and central regions sequentially moved to the right. The distribution curves of the southern and central regions were closely interlaced, indicating that the hospital efficiency levels in the southern and central regions are similar and significantly higher than the level in the northern region.

Second, the distribution curve of the efficiency density in northern hospitals peaks, and the distribution curves of the efficiency density for the central and southern hospitals displays broad kurtosis.

Finally, in terms of shape, the distribution curve of the efficiency density for northern hospitals is bimodal, and those for the central and southern hospitals are unimodal, suggesting that most hospitals in the central and southern regions have little difference in medical level, while the medical level of northern hospitals is polarized; this relation reflect the concept of “the strong get stronger, and the weak get weaker” (Matthew's effect).

Analysis of the Changes in Hospital Technical Efficiency Rankings

To show the changes in efficiency among the sample hospitals before and after the

implementation of quality constraints, the comprehensive efficiency values of sample hospitals under the two constraint conditions were ranked, and the changes in hospital rankings were compared. The results are shown in Figure 5. In the northern region, the ranking of hospital 17 increased the fastest, and the rankings of hospitals 6 and 13 decreased most obviously. In the central region, the ranking of hospital 24 increased the fastest, and the ranking of hospital 29 decreased the most. In the southern region, the ranking of hospital 71 increased the fastest, and the ranking of hospital 67 decreased the most.

By analyzing the unexpected outputs of adverse events at hospitals, it was found that the changes in efficiency rankings were related to the unexpected outputs of adverse events; notably, the efficiency ranking increased when the unexpected output level was low, and the ranking decreased when the unexpected output level was high. For example, the average unexpected output of hospitals in the northern region was -14.35, and that of hospital 17, with a medical quality higher than that of most hospitals, was -3.38. However, the average unexpected outputs of hospitals 6 and 13 were -23.78 and -31.08, respectively, and the corresponding medical quality was lower than that of other hospitals. Additionally, the average unexpected output values of hospitals in the central and southern regions were -15.3 and -19.22, respectively, and the average unexpected output values of hospitals 24 and 71 were only -3.09 and -3.49, respectively. Moreover, the average unexpected output values of hospitals 29 and 67 were -23.99 and -57.25, respectively.

The Spearman rank correlation test was used to determine whether there was a

correlation between the hospital efficiency values under the two different constraints. The significance level was 1%. The results showed that there was a positive correlation between the efficiency values of sample hospitals under the two constraints. According to the results, the three regions were different: the southern region had the highest similarity, with a correlation coefficient of 0.9673, and the greatest difference was observed in the northern region, with a correlation coefficient of 0.8452.

Discussion

This paper used the meta-frontier model and SBM-undesirable(Slacks-based Measurement-undesirable) model to calculate the efficiency of county-level public hospitals in Shanxi Province from 2013 to 2018. Then, we evaluated the reform effect and resource utilization rate of county hospitals and explored the influence of medical quality on hospital efficiency.

The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). In other studies, the average efficiency of county hospitals in Chongqing was 0.83 [12], in Anhui Province was 0.956 [19], and in China, as a mean value, was 0.7 [20], suggesting that the efficiency of county-level hospitals in Shanxi Province is obviously low; additionally, the utilization rate of existing resources is relatively low, and the technology used in inefficient. To improve the efficiency level of county-level hospitals, in addition to increasing investments to alleviate resource shortages, it is necessary to improve the utilization efficiency of resources, such as improving hospital management, rationally allocating human resources, and optimizing capital investments [35].

The results showed that the efficiency of county-level public hospitals in Shanxi Province did not improve and even declined in some areas from 2013 to 2018 (Figure 2C). Although the reform of county-level hospitals was initiated in 2012, the effect was not remarkable, as also noted by Jiang et al. [9]. Moreover, the study found that there were regional differences in the efficiency of county-level public hospitals in Shanxi Province. The efficiency level of county-level public hospitals in the central and southern regions of Shanxi Province was high, while the efficiency level in the northern region was comparatively low (Figure 2A and Figure 2C); these trends were also reflected by the technology gap ratio distribution in each region (Figure 1), which indicated that the county-level hospitals in the northern region were far from the technological frontier. Therefore, increasing the resource inputs for hospitals in the northern region of the province should be prioritized to improve their medical levels. Additionally, the population and economic level in northern Shanxi Province are lower than those in the central and southern regions [36]; thus, hospital efficiency may be related to the economic environment and population.

This study also showed that quality constraints had an important impact on hospital efficiency evaluation (Figures 3 and 4). Neglecting medical quality output could lead to underestimates of the hospital efficiency level. This finding could potentially be attributed to the fact that medical quality is often related to hospital management and human resources [37]. With improvements in hospital management and medical treatment ability, medical quality will also increase, as will the corresponding hospital efficiency. Improving the quality of medical services is often the goal of public hospitals [38], but many hospitals begin to expand blindly, resulting in inefficiency [20,39,40]. Pang [41] et al. noted that improperly scaled expansion can lead to technical efficiency in the short term but not in the long term. Therefore, to improve the medical quality level, increasing the technological capacity and improving management are steps.

Conclusion

This showed that after the implementation of county-level public hospital reform, the efficiency level of county-level public hospitals in Shanxi Province did not improve but remained low. Notably, the utilization rate of resources was low, and the reform effect was not obvious. There are differences in the efficiency of county-level hospitals in different regions, with the highest efficiency in the central region, the second-highest level in the southern region and the lowest level in the northern region. To improve the efficiency of hospitals, support to the northern region should be strengthened, hospital management should be improved, and health human resources should be rationally allocated.

The results also indicated that quality factors have a significant impact on hospital efficiency evaluation. The keys to improving the level of medical quality are to improve the proportion of technical personnel and the level of hospital management. The expansion of county-level hospitals should consider the economic level and service area in the region to avoid expansion and blind investment, potentially resulting in wasted resources.

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Authors' contribution

All authors made significant contribution to this study. JL conceptualized the study. WL collected and analyzed the data. BBG wrote the first draft of the manuscript. XJH、HKW and GYZ interpreted the results and revised the manuscript. The final version submitted for publication was read and approved by authors.

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Availability of data and materials

The data sets analyzed during this study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

Not Applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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figure legend in the figure

Figure 2:

According to the North

According to the Central

According to the South

According to the Entire

Figure 3:

According to the North

According to the Central

According to the South

According to the Entire

Figure 4:

According to the North

According to the Central

According to the South

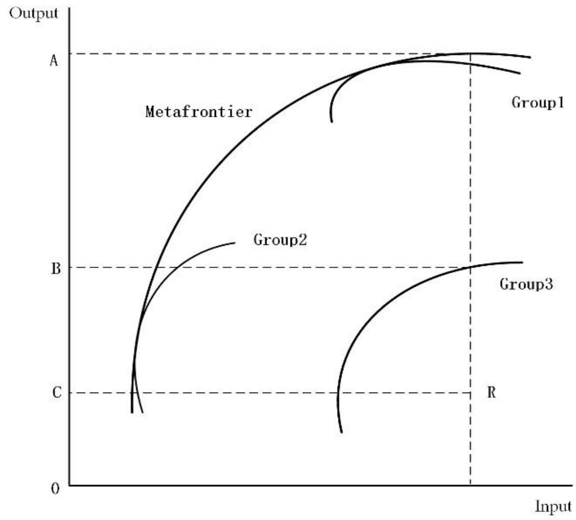

Fig 1 Schematic diagram of common frontier and group frontier

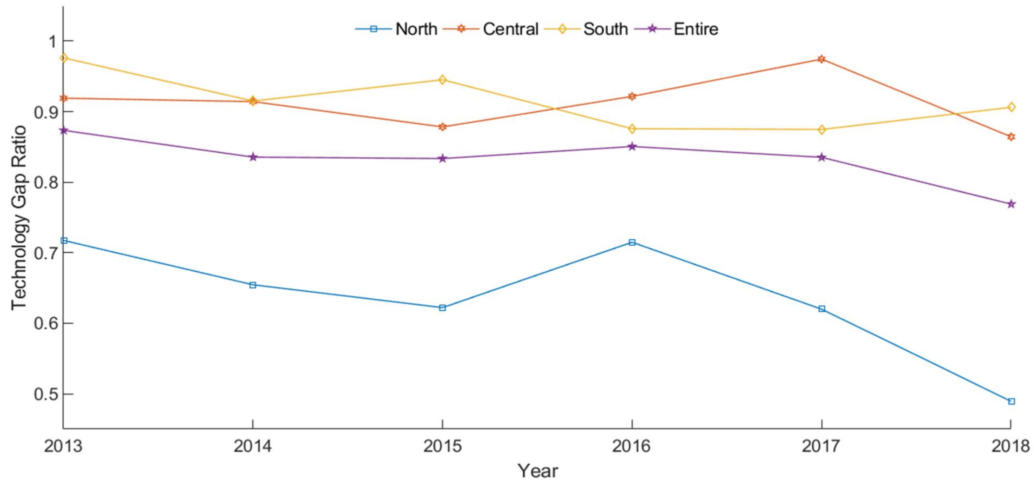

Fig.2 The technology gap ratios in northern, central and southern Shanxi Province from 2013 to 2018 under the quality constraint

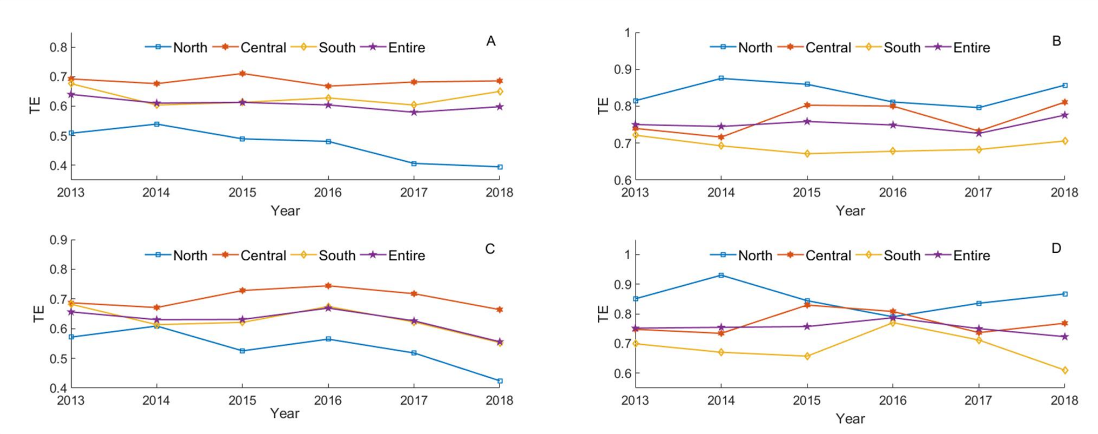

Fig.3 Efficiency changes of county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

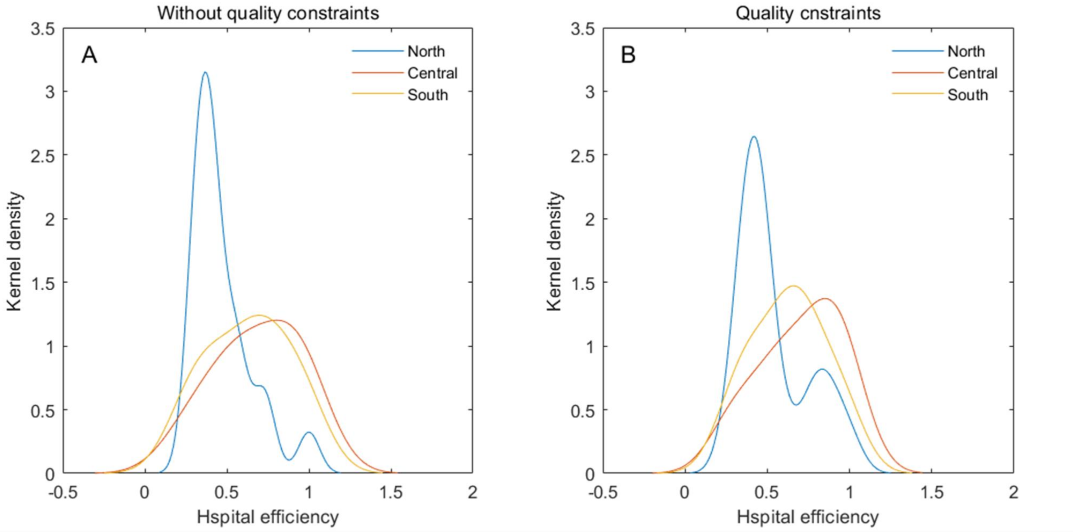

Fig.4 Distribution of the service efficiency of county-level public general hospitals in Shanxi Province

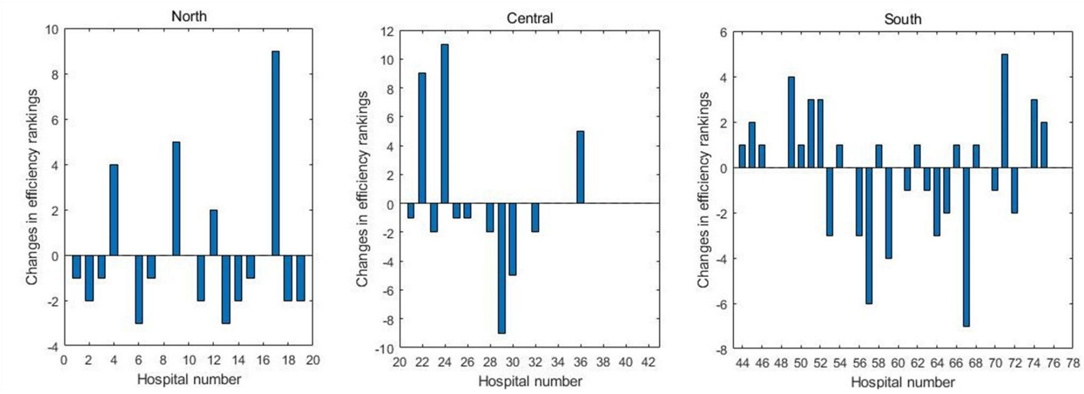

Fig.5 Charges in the efficiency ranking of county-level public general hospitals in Shanxi Province before and after the implementation of quality constraints

Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints: a cross-sectional study

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Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints: a cross-sectional study

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Abstract

Objectives: Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist.

Methods: Based on the data from 77 county-level public general hospitals (CPGHs) in Shanxi Province, China, from 2013-2018, we applied the meta-frontier and SBM-undesirable（Slacks-based Measurement-undesirable） DEA(Data Envelopment Analysis) model to measure the CPGHs' medical service efficiency with or without medical quality constraints and evaluate the effects of the new medical reform to explore the utilization of health resources and look for ways to improve the CPGHs' medical service efficiency. Moreover, we analyze the factors affecting public hospital efficiency based on the FRM model.

Results : The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54). Factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income.

Conclusion: To improve CPGHs' medical service efficiency, the government should increase investment in the northern region, and hospitals should improve the management level and allocate human resources rationally.

Keywords: County-level Hospital Efficiency, Medical quality, Meta-frontier DEA Model, SBM-Undesirable DEA Model.

Strengths and limitations of this study

- The Meta-frontier and SBM-undesirable DEA models effectively solved the problem that the efficiency score of hospitals was not on the same production frontier.
- Medical quality index was set as an output indicator in this study, which means that the hospitals should not only focus on the number of patients, but also focus on the

medical quality.

- Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.

Background

In March 2009, the Chinese government started a new medical reform. Since the implementation of the medical reform, China has made great achievements in expanding medical security services [1,2]. The government has vigorously developed primary medical and health services and strived to improve the fairness of the health service distribution [3]. However, the distribution of health resources in China is still unreasonable, and health resources are scarce [4]. High-quality medical resources are mainly concentrated in cities, leading to a significant medical quality gap between urban and rural hospitals [5-7]. Additionally, patients prefer to choose urban hospitals, which leads to the idleness of rural hospital resources [8]. Health resource waste and shortage issues have seriously restricted the service ability of medical and health institutions and led to low medical efficiency [9]. To solve these problems and improve the quality of medical services, the government has implemented a series of reforms in rural hospitals [1,10]. China's urban and rural medical system is mainly composed of urban tertiary hospitals, urban community hospitals, county-level hospitals and township health centers [11]. Among them, county-level public general hospitals (CPGHs) act as a link between China's urban and rural medical systems, and they are the leaders of rural health institutions [12-14]. Their medical services have a wide range of radiation and cover a large population [9]. However, county-level hospitals also have problems such as shortages of human resources, low levels of medical services and uneven distributions of resources [14-16]. For example, Wu noted that the quality of human resources in primary hospitals is not high and the medical service level is poor [17]. Jay found that the average resource levels of county-level hospitals in western China were lower than those in other regions [18]. Therefore, it is very important to improve the utilization rate of primary health resources and the medical efficiency of county-level hospitals.

In recent years, many scholars have studied the medical efficiency of CPGHs in China. Li measured the medical efficiency of 12 CPGHs in Anhui Province and found that it has declined year by year; additionally, the medical reform effect of CPGHs was not significant [19]. Wang analyzed the medical efficiency of 127 CPGHs in China and found that the efficiency of CPGHs still has considerable room for improvement [20]. Jiang conducted a study of 1105 CPGHs in China and noted that although medical reform has increased the scale of hospitals, it has not improved the medical efficiency of CPGHs [9]. Other scholars' studies have also shown that the medical efficiency of CPGHs has room for improvement [12,21,22]. Super SBM-undesirable（Slacks-based Measurement-undesirable） DEA(Data Envelopment Analysis) model was used by A. Monzeli to measure the hospital's emergency departments, which indicated that the undesirable output can determine the hospitals' efficiency [23].

In a review of the previous literature on the medical efficiency of CPGHs, we found the following defects. 1. In China, county-level hospitals are divided into CPGHs, traditional Chinese medical hospitals, and maternal and child health care hospitals. However, most studies do not subdivide the hospitals by type. Bates [24] found that different types of hospitals have different resource allocation and output structures. 2. Most studies have not considered the differences in production frontiers due to the different natural, social and economic environments in different regions. However, in other industries, some relevant scholars have added relevant non-expected output indicators for research when evaluating efficiency. In 2012, Majid Azadi [25] used the SBM-Undesirable DEA model to evaluate the efficiency of suppliers with adverse events, No. Of personnel and Average time for serving customers (HR) were selected as input indicators and Profit margin as expected output. No. Of Dissatisfied customers were considered as Undesirable outputs, and the results showed that the SBM-Undesirable DEA model could help decision makers choose suitable suppliers. In 2021, Tong Guang Ji [26] evaluated agro-ecological efficiency in 136 developing countries using the SBM-Undesirable DEA model, Input indicators include Freshwater consumption, Agricultural land area, and Fertilizer consumption and Labor; expected output indicators include Production and Forest area. Non-expected output indicators were selected as Methane emissions and Nitrous oxide emissions. The results show that choosing an effective marginal tradeoff does not reduce the relative efficiency of dMU below the effective boundary line. Thus, this approach enables decision makers to determine the optimal marginal tradeoff point for optimal efficiency and to determine which output factors require specialized brainstorming to design effective policies. Therefore, if the DEA (Data Envelopment Analysis) method is used to measure the medical efficiency of hospitals located in different regions, it will not be able to capture the technical heterogeneities among them, and the efficiency scores of the hospitals may not be accurate. 3. Ignoring the constraints of medical quality, which is an unexpected output of DEA, will seriously affect hospital efficiency. However, many studies have not considered the issue of unexpected output.

Based on these defects, this study makes the following improvements: 1. the medical efficiency of 77 CPGHs, not including other types of county-level hospitals, is evaluated; 2. the meta-frontier DEA model is used to evaluate the medical efficiency of CPGHs in different regions and solve the problem of technical heterogeneity; and 3. "adverse events" are selected as a medical quality indicator. Finally, the SBM-undesirable DEA model is used to solve the problems related to unexpected outputs categorized as "adverse events".

Methods

Data Sources

The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected [27]. The data excluded other types of hospitals, such as traditional Chinese medical hospitals, maternal and child health care hospitals and other medical institutions, so they met the homogeneity requirement of the DEA(Data Envelopment Analysis) method.

Meta-frontier and Group Frontier DEA Models

The meta-frontier DEA model was first proposed by Battese [28]. The meta-frontier refers to the potential technical level of all decision making units (DMUs), and the group frontier refers to the actual technical level of each DMU. The difference between them is the different technology sets to which they refer.

According to the meta-frontier DEA model of Battese [29], we took the unexpected output into account. In this case, the technology set (T^{meta}) includes all technically feasible input-output combinations:

$$T^{meta} = \left\{ \begin{matrix} (x,y,b):x \geq 0,y \geq 0,b \geq 0; \\ x\ can\ produce\ \ (y,b) \end{matrix} \right\} \tag{1}$$

In the above formulation, *x* is the input vector, *y* is the expected output vector, and *b* is the unexpected output vector. That is, to obtain a certain output P^{meta} *(y, b)*, the input *(x)* must be satisfied under the given technological condition *(T^{meta})*. The production possibility set (meta-frontier) is as follows:

$$P^{meta}(x) = \{(y,b) : (x,y,b) \in T^{meta}\} \tag{2}$$

Therefore, the technical efficiency function of the meta-frontier from the perspective of the output can be expressed as follows:

$$TE^{meta}(x,y,b) = inf_{\beta}\{\beta > 0 : (y/\beta) \in P^{meta}(y,b)\} \tag{3}$$

According to the different levels of economic development, Shanxi Province is divided into three groups: Northern Shanxi, Central Shanxi and Southern Shanxi *(h=1, 2, 3)*. The group technology set is:

$$T^h = \{(x_h,y_h,b_h):x_h \geq 0,y_h \geq 0,b_h \geq 0;x_h \rightarrow (y_h,b_h)\},h = 1,2,3 \tag{4}$$

The production set is as follows:

$$P^h(x_h) = \{(y_h,b_h):(x_h,y_h,b_h) \in T^h\},h = 1,2,3 \tag{5}$$

The group technical efficiency *(h=1,2,3)* can be expressed as:

$$TE^{h}(x_h,y_h,b_h) = inf_{\beta}\{\beta > 0:(y_h/\beta) \in P^{h}(y_h,b_h)\},h = 1,2,3 \qquad (6)$$

Meta-frontier technology is the envelope curve of the group frontier technology. So:$T^{m} = \{T^{1} \cup T^{2} \cup T^{3}\}$.

Technology Gap Ratio (TGR)

The technology gap ratio [28] can be expressed by the meta-frontier and group technology efficiency functions (The results are shown in Figure 1):

$$TGR^{h}(x_h,y_h,b_h) = \frac{TE^{meta}(x,y,b)}{TE^{h}(x_h,y_h,b_h)},h = 1,2,3 \qquad (7)$$

Fig 1 Schematic diagram of common frontier and group frontier

Take R Hospital located in Group3 as an example, then

$$TE^{meta}(R) = \frac{OC}{OA};TE^{h}(R) = \frac{OC}{OB};TGR^{h}(R) = \frac{TE^{meta}}{TE^{h}} = \frac{OC/OA}{OC/OB} = \frac{OB}{OA} \qquad (8)$$

If the TGR is less than 1 or there are obvious differences between the mean values of TE^{meta} and TE^{h}, it is necessary to divide the CPGHs into different groups. In contrast, if the TGR is close to 1 or there are no obvious differences between the mean values of TE^{meta} and TE^{h}, there is no need to divide the CPGHs into different groups.

SBM-undesirable DEA Model

The SBM-undesirable（Slacks-based Measurement-undesirable） DEA model [30] of unexpected output is used to construct the efficiency measurement model under the meta-frontier and group frontier conditions, and the formula is:

$$\rho^{*} = min\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_{i0}^{-}}{x_{i0}}}{1+\frac{1}{S}\left(\sum_{r=1}^{S_1}\frac{s_r^{g}}{y_{r0}^{g}}+\sum_{r=1}^{S_2}\frac{s_r^{b}}{y_{r0}^{b}}\right)}$$

Subject to

$$x_0 = X\lambda + S^{-}$$

$$y_0^g = Y\lambda - S^g$$

$$y_0^b = Y\lambda + S^b$$

$$L \le e\lambda \le U$$

$$S^-, S^g, S^b, \lambda \ge 0. \tag{9}$$

In the above formulation, *X*, *Y* and *B* represent the input and output vectors of different CPGHs each year. The meta-frontier represents 77 county regions, and the group frontier represents different groups in the 77 county regions; s^-, s^y and s^b are slack variables related to the input, expected output and unexpected output, respectively; *r* represents the *r*-th DMU; and r^0 represents the DMU to be assessed. The objective function ρ^* decreases with $s_h^-(\forall h), s_r^y(\forall r)$ and $s_r^b(\forall r)$, where $0 < \rho^* \le 1$.

Because the data are from multiple years, homogeneity for each CPGH and statistical relations should be considered. Therefore, we adopted the global reference model proposed by Pastor and Lovell [31] to calculate the Malmquist index. This model can solve the comparability problem caused by considering different frontiers in efficiency evaluation.

Disease Complexity Adjustment for Discharged Patients

Since the disease complexity varies from hospital to hospital, it is unfair to simply input the approximate number of discharged patients into the input-output index. For example, hospitals with high technology levels are likely to treat patients with complicated conditions, and these hospitals will take more time to treat such a patient than to treat a patient with a mild illness. Hospitals with low technology levels can supply health services to patients with mild illness or light symptoms as a result of their limited technical capacities, and patients with severe illness may prefer directly seeking health services at high-level hospitals. Thus, 1000 patients in hospital-A will all have difficult and complicated diseases, and those in hospital-B will have mild diseases. However, when performing efficiency evaluation research, if a quantity of units 1000 is input without considering the complexity of the disease, it would be unfair to hospitals with high technical levels. However, the RCI index can be used to adjust the numbers of discharged patients according to the average length of stay and bed utilization rate [32]. Given the poor quality of the patient records in county-level hospitals, we select the RCI index, which provides a reference for efficiency evaluation in underdeveloped areas. The specific adjustment methods were as follows:

$$RCI_i = ALoS_i * (OCC_i/OCC_s) \qquad (10)$$

In the above formula, $ALoS_i$ refers to the average length of stay in the *i*-th hospital, OCC_i refers to the bed utilization rate of the *i*-th hospital, and OCC_s refers to the average bed utilization rate of all evaluated hospitals. Therefore, the average length of stay will be adjusted upward for hospitals with higher bed utilization rates than the average. The actual number of discharged patients (P) was adjusted based on the RCI of each hospital, and finally, the number of discharged patients (EP) adjusted according to the RCI index was obtained. The formula is as follows:

$$EP = P * (RCI_i/RCI_s) \qquad (11)$$

FRM (Fractional Response Model)

The regression equation is:

$$EFFICIENCY_{it} = \beta_0 + \beta_1 ln\, INCOME_{it} + \beta_2 ln\, POPULATION_{it} + \beta_3$$

$$ln\,SUBIDY_{it} + \beta_4 ln\,DAY_{it} + \beta_5 BEDRATIO_{it} + \beta_6 STAFFRATIO_{it} + \varepsilon_{it} \qquad (12)$$

where $EFFICIENCY_{it}$ represents the service efficiency of the hospital i in year t, β_0 is a constant term. $INCOME_{it}$ and $POPULATION_{it}$ represent the per capita disposable income and residents population of the district (county) where the hospital i is located in year t, respectively; $SUBIDY_{it}$, DAY_{it},$BEDRATIO_{it}$and $STAFFRATIO_{it}$ represent the subsidy, average length of hospital stay, hospital bed utilization rate and the proportion of health technicians, respectively. ε_{it} is the error term. This paper uses Stata16.0 software for data processing and regression.

To examine the factors that influence the service efficiency of public hospitals, this paper uses the panel Tobit model with right-side restriction for regression. One of the defects of the Tobit model is that it has a strong dependence on distribution and is sensitive to the problem of heteroscedasticity. If the error term does not follow the normal distribution or has a heteroscedasticity issue, the estimation will be inconsistent [33]. In addition, there are some problems in using the Tobit model to analyze the factors of hospital efficiency [34]. In fact, the hospital efficiency in this paper is a natural consequence of the way DEA is defined, and the hospital efficiency measured according to the Non-oriented EBM model is inherently between 0 and 1, which is not because of the Tobit model that set the efficiency greater than 1 to the value of 1.

Papke and Wooldridge [35] proposed the Fractional Response Model (FRM) in 1996, which overcomes many of the limitations of linear and nonlinear econometric models when studying bounded data. Ramalho et.al. [36] further developed the FRM model. The FRM model is a nonlinear model using the Quasi-Maximum Likelihood

Estimation (QMLE). Compared with the Tobit model, the QMLE is asymptotically efficient and consistent because the FRM model does not require distributional or heteroskedasticity assumptions on the DEA score [37]. In addition, the advantages of the FRM model are that it allows a nonlinear relationship between hospital efficiency and its determinants, allows error terms to have autocorrelation, and does not allow the efficiency score to fall outside 0-1, which are in line with the research content of this paper. To this end, this paper uses the Fractional Response Model (FRM) for robustness testing. The specification is:

$$E(y_i|\boldsymbol{x_i}) = G(\boldsymbol{x_i}\boldsymbol{\beta}) \tag{13}$$

where the subscript i represents hospital, $\boldsymbol{x_i}$ are the factors, and $\boldsymbol{\beta}$ is the parameter to be estimated. $G(\eta) = exp(\eta)/[1 + exp(\eta)]$ represents a probability distribution function in the form of Logit whose domain is all real numbers and whose range is (0,1).

Referring to Papke & Wooldridge [35], the log-likelihood equation can be estimated by Quasi maximum likelihood estimation (QMLE):

$$l_i(\boldsymbol{\beta}) = y_i ln\,[G(\boldsymbol{x_i}\boldsymbol{\beta})] + (1-y_i) ln\,[1-G(\boldsymbol{x_i}\boldsymbol{\beta})] \tag{14}$$

Finally, maximize Equation (15) to obtain the value of $\boldsymbol{\beta}$ in Equation (13).

$$\max_{\boldsymbol{\beta}} \sum_{i=1}^{269} l_i(\boldsymbol{\beta}) \tag{15}$$

Patient and public involvement

No patient involved

Results and Analysis

Variable Selection

The variables were selected according to previous empirical research and the literature [7, 9, 12, 19-22]. Input variables usually include labor and capital [38]. In our study, the numbers of registered doctors and registered nurses were used to represent the elements of human resources as input variables. Beds and equipment valued above 10,000 yuan were used as capital elements. The total visits, the number of discharged patients (EP) adjusted by the RCI and the number of operations were used as output variables. The number of adverse events was used to replace the unexpected output variable as a quality index [39]. The descriptive statistics of the input-output indicators are shown in Table 1.

Table 1. Descriptive statistics

Input/output	Variable	**Mean**	**Std. Dev.**	Min	Max
Input variables	doctor	95.232	42.017	18	278
	nurse	117.985	71.658	9	390
	bed	250.217	125.748	80	790
	machine	226.736	145.973	35	831
Desirable output variables	treatment	95432.120	58710.450	16351	292534
	EP	9607.892	6610.737	756.4231	32707.7
	operations	1470.729	1189.186	81	7926
Undesirable output variables	adverse events	68.712	38.462	10	200

Note: The sample size in the model was 462

The variables for FRM, the dependent variable is the service efficiency of public hospitals. As for the independent variables, according to the existing literature and the consideration of data availability and sample size, the following six types of factors affecting the service efficiency of county-level public hospitals were selected for analysis, including (1) External factors: per capita disposable income of residents (county-level economic factor), number of usual residents (county-level population factor); (2) Internal factors: financial subsidy income (hospital-level financial factor), the proportion of health technicians (human resource factor), hospital bed utilization rate (equipment implementation factor), average length of hospital stay (service delivery factor). The summary of variables for FRM is shown in Table 2.

Table 2. Summary of variables for FRM

Variable name	Variable	Definition
Hospital service efficiency	*EFFICIENCY*	Service efficiency of each county-level public hospital calculated according to the Non-oriented EBM model
Per capita disposable income (yuan)	*INCOME*	Per capita disposable income of usual residents
Resident population (person)	*POPULATION*	Population of usual residents
Financial subsidy income (ten thousand yuan)	*SUBSIDY*	Financial subsidy received by hospitals
Average length of hospital stay	*DAY*	$\frac{\text{Number of days that beds are occupied by dischargers}}{\text{Number of people discharged}}$
Utilization rate hospital bed	*BEDRATIO*	$\frac{\text{Number of days that beds are actually occupied}}{\text{Number of days that beds are available}}$
Proportion of health technicians	*STAFFRATIO*	$\frac{Number\ of\ \text{Inspection Technician and Imaging Technician}}{Number\ of\ employees}$

Test and Analysis of the Technology Gap Ratio (TGR)

Under a quality constraint, a mean value comparison test of the obtained technology gap ratio (TGR) was performed, as shown in Table 3. Assuming that the mean value was 1 and the significance level was 95%, the results showed that the average TGR of each group was less than 1. After performing calculations, from 2013 to 2018, the mean value of the hospital TGR in the southern group was at the highest level, close to 1, reaching 0.93, followed by that of the central group of 0.91, and finally that of the northern group at only 0.63. This result indicated that the southern group was closest to the meta-frontier of technology in county-level public general hospitals, followed by the central group and the northern group. Obviously, both the overall TGR and the regional TGR values were significantly different from the assumed mean value of 1. Therefore, the heterogeneity of the division of public hospitals in Shanxi Province was very obvious, and this finding agreed on the conditions of the DEA meta-frontier model; thus, the meta-frontier model could be suitably applied to analyze the results.

Table 3. Comparative test results of the mean value of the technology gap among county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

Region	Mean TGR	t	P
North	0.62649	-17.2815	0.000
Central	0.907907	-8.9249	0.000
South	0.9328708	-6.9778	0.000
Entire	0.8494894	-15.6809	0.000

After calculating the efficiency of county-level general hospitals in Shanxi Province under meta-frontier and group frontier conditions, the temporal trends of the technology gaps in the north, central and southern regions under the quality constraint were further compared. The results are shown in Figure 2.

Figure 2 shows that the mean value of the TGR in the southern and central regions of Shanxi Province was high, while that in the northern region was the lowest, indicating that the central and southern regions provide better hospital management and medical levels as a whole than did the northern region; additionally, they are closer to the technological frontier. The mean value of the TGR in the central and southern regions fluctuated at a high level and remained in a basically stable state, but the mean value of the TGR in the northern region considerably changed. Except for a slight increase in the mean TGR in 2016, other years experienced a downward trend, which indicated that the medical level in the northern region decreased and that different frontiers influenced the efficiency of county-level public general hospitals in different regions of Shanxi Province.

Time Series Analysis of the Technical Efficiency of Hospitals

Figures 3A and B show the trend of the average comprehensive efficiency of sample hospitals in Shanxi Province and in three major regions from 2013-2018 under the meta-frontier and group frontier, respectively. Taking the meta-frontier in Figure 3A as a reference, the overall average medical service efficiency of county-level public general hospitals was more than 0.6, and the medical service efficiency in each region was relatively stable each year; notably, the efficiency in the northern region displayed a slow downward trend. Referring to Figure 3B, the overall average efficiency for the group frontier was approximately 0.75, the southern region was relatively stable, and the trends in the northern and central regions involved inverted U-shaped curves in the early stage; however, all the regions experienced a significant increase in 2018.

Figures 3C and D show the trend of the average comprehensive efficiency of the sample hospitals in Shanxi Province and in three major regions under the meta-frontier and the group frontier conditions, respectively, based on the quality constraints from 2013 to 2018. Taking the common frontier in Figure 3C as a reference, the overall average medical service efficiency of county-level public general hospitals was approximately 0.63, and the medical service efficiency trend in various regions displayed an inverted U-shaped curve in each year; that is, it fluctuated and rose from 2013 to 2016 and then dropped rapidly after 2016. Regarding Figure 3D, the overall average efficiency under the group frontier was approximately 0.75, and the medical service efficiency trend in the northern region displayed a U-shaped curve that fluctuated and decreased from 2013 to 2016 and then rose slowly after 2016. Moreover, the efficiency trends in the central and southern regions were the same as those for the meta-frontier.

Analysis of the Differences in Hospital Technical Efficiency

The distribution of the service efficiency of public general hospitals in Shanxi Province is shown in Figure 4. Graph A shows the distribution of hospital efficiency without quality constraints, and graph B presents the distribution of hospital efficiency under quality constraints. In terms of location, the peak position of the distribution curve in Figure 4B moves to the right compared with that in Figure 4A, indicating an overall efficiency improvement. The kurtosis of the distribution curve for the central and southern regions in Figure 4B is greater than that in Figure 4A, indicating that the

distribution of the efficiency was more concentrated in B. The northern distribution curve in Figure 4B displays an obvious bimodal state, indicating that the efficiency distribution was somewhat scattered. Therefore, quality constraints were very important in the hospital efficiency evaluation. A lack of quality constraints would lead to certain deviations in the evaluation results, and the results would not comprehensively reflect the actual operation status of the medical system.

An analysis of the hospital efficiency distribution in Figure 4B was performed. First, for the location, the distribution curves of the hospital efficiency density in the northern, southern and central regions sequentially moved to the right. The distribution curves of the southern and central regions were closely interlaced, indicating that the hospital efficiency levels in the southern and central regions are similar and significantly higher than the level in the northern region.

Second, the distribution curve of the efficiency density in northern hospitals peaks, and the distribution curves of the efficiency density for the central and southern hospitals displays broad kurtosis.

Finally, in terms of shape, the distribution curve of the efficiency density for northern hospitals is bimodal, and those for the central and southern hospitals are unimodal, suggesting that most hospitals in the central and southern regions have little difference in medical level, while the medical level of northern hospitals is polarized; this relation reflects the concept of “the strong get stronger, and the weak get weaker” (Matthew's effect).

Analysis of the Changes in Hospital Technical Efficiency Rankings

To show the changes in efficiency among the sample hospitals before and after the

implementation of quality constraints, the comprehensive efficiency values of sample hospitals under the two constraint conditions were ranked, and the changes in hospital rankings were compared. The results are shown in Figure 5. In the northern region, the ranking of hospital 17 increased the fastest, and the rankings of hospitals 6 and 13 decreased most obviously. In the central region, the ranking of hospital 24 increased the fastest, and the ranking of hospital 29 decreased the most. In the southern region, the ranking of hospital 71 increased the fastest, and the ranking of hospital 67 decreased the most.

By analyzing the unexpected outputs of adverse events at hospitals, it was found that the changes in efficiency rankings were related to the unexpected outputs of adverse events; notably, the efficiency ranking increased when the unexpected output level was low, and the ranking decreased when the unexpected output level was high. For example, the average unexpected output of hospitals in the northern region was -14.35, and that of hospital 17, with a medical quality higher than that of most hospitals, was -3.38. However, the average unexpected outputs of hospitals 6 and 13 were -23.78 and -31.08, respectively, and the corresponding medical quality was lower than that of other hospitals. Additionally, the average unexpected output values of hospitals in the central and southern regions were -15.3 and -19.22, respectively, and the average unexpected output values of hospitals 24 and 71 were only -3.09 and -3.49, respectively. Moreover, the average unexpected output values of hospitals 29 and 67 were -23.99 and -57.25, respectively.

The Spearman rank correlation test was used to determine whether there was a

correlation between the hospital efficiency values under the two different constraints. The significance level was 1%. The results showed that there was a positive correlation between the efficiency values of sample hospitals under the two constraints. According to the results, the three regions were different: the southern region had the highest similarity, with a correlation coefficient of 0.9673, and the greatest difference was observed in the northern region, with a correlation coefficient of 0.8452.

Analysis of factors affecting public hospital efficiency

The result on factors affecting public hospital efficiency based on the FRM model is shown in Table 4.

Table 4. Regression result of the FRM model

	(1)FRM-Logit	(2)FRM-Logit
Constant	-63.1201 (57.5153)	174.6323^{**} (69.2530)
ln *INCOME*	23.9425^{***} (8.0147)	57.9482^{***} (9.1432)
ln *POPULATION*	11.7407^{**} (4.8335)	18.0447^{***} (4.9030)
ln *SUBSIDY*	18.2966^{***} (2.1988)	13.6022^{***} (2.1659)
ln *DAY*	-53.1396^{***} (8.9505)	-53.4437^{***} (8.9724)
BEDRATIO	1.8526^{***} (0.1080)	1.8717^{***} (0.1104)
STAFFRATIO	4.3761^{***} (1.1724)	3.9982^{***} (1.1333)
Wald test	570.78(0.0000)	758.54(0.0000)
Time fixed effect	No	Yes
County fixed effect	No	Yes
Hospital category effect	No	Yes
Observations	1430	1430

Note: The data in parentheses after each coefficient is the standard deviation. To facilitate comparison with the Tobit model, both coefficients and standard deviation are multiplied by 100. In the Wald test, the values on the left side of the parentheses are the values of χ^2 distribution, and the values in the parentheses are the corresponding P values. ***, **, and * represent 1%, 5%, and 10% significance level, respectively.

We can find that the coefficient of per capita income is positive and significant, that is, the improvement of residents' per capita disposable income can improve the service efficiency of county public hospitals; Population factor negatively impacts public hospital efficiency when the fixed effects are not controlled. After controlling for the fixed effects, the coefficient is significantly positive, that is, the resident population in the county where the hospital is located is positively correlated with the service efficiency of county public hospitals; The effect of financial subsidy income on the service efficiency of county public hospitals is significantly positive; The coefficient for the average length of hospital stay is the largest and significantly negative; And the proportion of health technicians has a significant positive impact on the service efficiency of public hospitals.

Discussion

This paper used the meta-frontier model and SBM-undesirable (Slacks-based Measurement-undesirable) model to calculate the efficiency of county-level public hospitals in Shanxi Province from 2013 to 2018. Then, we evaluated the reform effect and resource utilization rate of county hospitals and explored the influence of medical quality on hospital efficiency. Moreover, we analyze the factors affecting public hospital efficiency based on the FRM model.

The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). In other studies, the average efficiency of county hospitals in Chongqing was 0.83 [12], in Anhui Province was 0.956 [19], and in China, as a mean value, was 0.7 [20], suggesting that the efficiency of county-level hospitals in Shanxi Province is obviously low; additionally, the utilization rate of existing resources is relatively low, and the technology used in inefficient. To improve the efficiency level of county-level hospitals, in addition to increasing investments to alleviate resource shortages, it is necessary to improve the utilization efficiency of resources, such as improving hospital management, rationally allocating human resources, and optimizing capital investments [40].

The results showed that the efficiency of county-level public hospitals in Shanxi Province did not improve and even declined in some areas from 2013 to 2018 (Figure 2C). Although the reform of county-level hospitals was initiated in 2012, the effect was not remarkable, as also noted by Jiang et al. [9]. Moreover, the study found that there were regional differences in the efficiency of county-level public hospitals in Shanxi Province. The efficiency level of county-level public hospitals in the central and southern regions of Shanxi Province was high, while the efficiency level in the northern region was comparatively low (Figure 2A and Figure 2C); these trends were also reflected by the technology gap ratio distribution in each region (Figure 1), which indicated that the county-level hospitals in the northern region were far from the technological frontier. Therefore, increasing the resource inputs for hospitals in the northern region of the province should be prioritized to improve their medical levels. Additionally, the population and economic level in northern Shanxi Province are lower than those in the central and southern regions [41]; thus, hospital efficiency may be related to the economic environment and population.

This study also showed that quality constraints had an important impact on hospital efficiency evaluation (Figures 3 and 4). Neglecting medical quality output could lead to underestimates of the hospital efficiency level. This finding could potentially be attributed to the fact that medical quality is often related to hospital management and human resources [42]. With improvements in hospital management and medical treatment ability, medical quality will also increase, as will the corresponding hospital efficiency. Improving the quality of medical services is often the goal of public hospitals [43], but many hospitals begin to expand blindly, resulting in inefficiency [20,44,45]. Pang [46] et al. noted that improperly scaled expansion can lead to technical efficiency in the short term but not in the long term. Therefore, to improve the medical quality level, increasing the technological capacity and improving management are steps.

For the factors that influence public hospital efficiency, firstly, when the per capita disposable income of residents is high, people may pay more attention to their health, and have more requirements for the service and technical level of the hospital. Accordingly, health services will be used more rationally. Secondly, the more resident population in the region, the greater the intensity of the demand for medical services, and the hospital will continuously improve its medical service to meet the demand, thus making the hospital service more efficient. The reason for the low level of significance level is that: on the one hand, the resident population is the macro-level data, which has little impact on the efficiency of the micro-level hospital; on the other hand, the mobility of people seeking medical treatment is high, so the population of the area where the hospital is located has limited effect on the efficiency of the local hospital. Thirdly, if the government increases the financial investment in the hospital, it will help the hospital to introduce high-tech equipment and improve the hospital's infrastructure construction capacity, etc. Thus it will prompt the hospital to realize the rational allocation of resources under the guidance of the government's policy of increasing the corresponding investment. As a result, the hospital achieves more efficient health service, improving the efficiency of hospital services. Fourthly, the average length of hospital stay is an important factor affecting the service efficiency of public hospitals, and a longer length of hospital stay will reduce the service efficiency level of the hospital. This may be because a longer length of hospital stay means hospitals are not treating patients in a timely manner or have to deal with more severe cases, making hospital services less efficient. Fifthly, the bed utilization rate reflects the vacant beds in the hospital. The higher the hospital bed utilization rate, the more patients can be provided with hospital-stay services at the same time, thereby increasing the hospital-stay service output and improving the hospital's service efficiency. Sixthly, for the positive impact of the proportion of health technicians, the reason may be that the higher the proportion of health technicians, the higher the level of medical service, and the further improvement of the service efficiency of the hospital.

Limitations

This study evaluated the efficiency of county public hospitals in Shanxi Province and explored the influence of scale on hospital efficiency. It provided a reference for the government and hospitals to reasonably control bed size. However, the study has Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.

Conclusion

This showed that after the implementation of county-level public hospital reform, the efficiency level of county-level public hospitals in Shanxi Province did not improve but remained low. Notably, the utilization rate of resources was low, and the reform effect was not obvious. There are differences in the efficiency of county-level hospitals in different regions, with the highest efficiency in the central region, the second-highest level in the southern region and the lowest level in the northern region. To improve the efficiency of hospitals, support to the northern region should be strengthened, hospital management should be improved, and health human resources should be rationally allocated.

The results also indicated that quality factors have a significant impact on hospital efficiency evaluation. The keys to improving the level of medical quality are to improve the proportion of technical personnel and the level of hospital management. The expansion of county-level hospitals should consider the economic level and service area in the region to avoid expansion and blind investment, potentially resulting in wasted resources.

According to the FRM regression results, it is concluded that the factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income. Shortening the average hospital stay can improve hospital efficiency. In areas with higher per capita disposable income of residents, the service efficiency of county-level public hospitals is higher. And the increase in subsidy has a positive effect on the improvement of hospital service efficiency. In addition, the county population, bed utilization rate and the proportion of health technicians also have significant impacts on hospital service efficiency. The higher the population, the higher the hospital efficiency. Increasing the bed utilization rate and the proportion of health technicians will also promote hospital service efficiency. However, only 77 hospitals in one province were selected for this study, so the extrapolation from this study may be limited.

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Authors' contribution

All authors made significant contribution to this study. JL conceptualized the study. WL collected and analyzed the data. BBG wrote the first draft of the manuscript. XJH、HKW and GYZ interpreted the results and revised the manuscript. The final version submitted for publication was read and approved by authors.

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Data Availability Statement

Data are available in a public, open access repository.

i) The data are mainly from the 2013-2019 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook, Overall 77 CPGHs in Shanxi Province were selected.

ii) The data is held in Baidu web disk. (Link: https://pan.baidu.com/s/1Z8TraRG2naSXTBqNJ04EAQ; Extraction code: VX3b)

iii) There are no reuse conditions for the data.

Ethics approval and consent to participate

Not Applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figure 2:

According to the North

According to the Central

According to the South

According to the Entire

Figure 3:

According to the North

According to the Central

According to the South

According to the Entire

Figure 4:

According to the North

According to the Central

According to the South

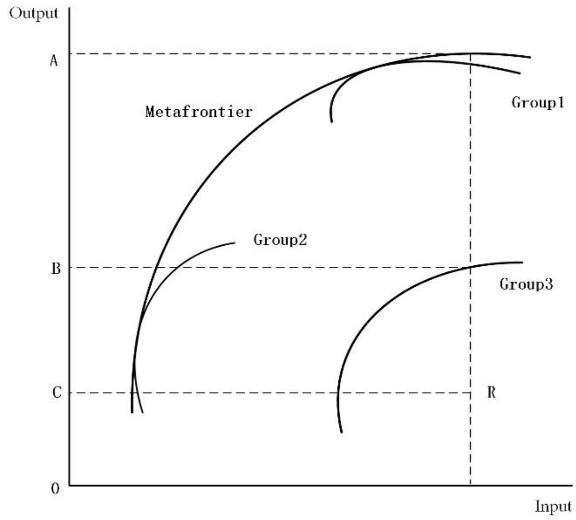

Fig 1 Schematic diagram of common frontier and group frontier

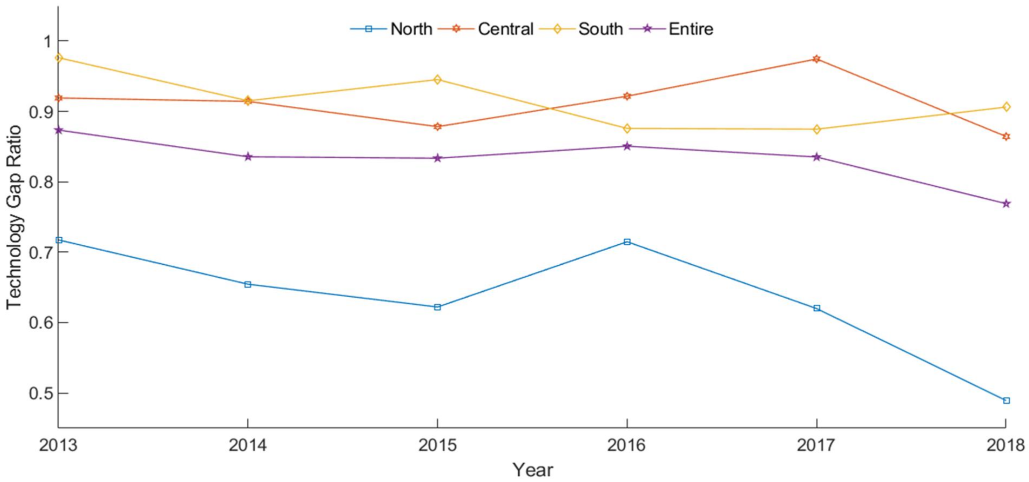

Fig.2 The technology gap ratios in northern, central and southern Shanxi Province from 2013 to 2018 under the quality constraint

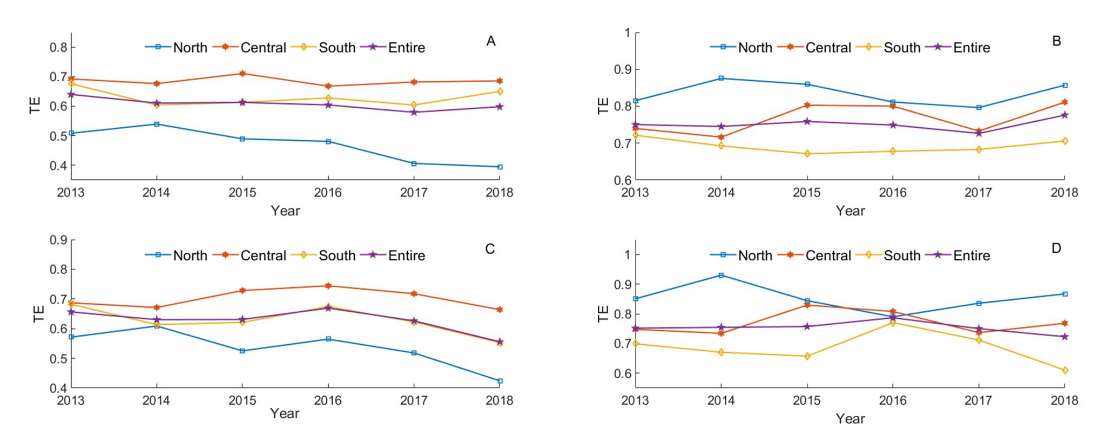

Fig.3 Efficiency changes of county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

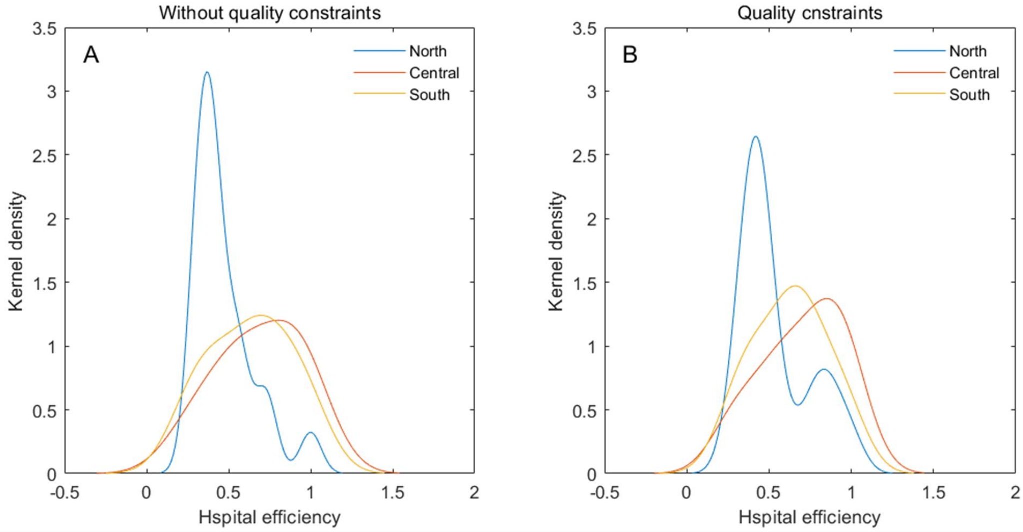

Fig.4 Distribution of the service efficiency of county-level public general hospitals in Shanxi Province

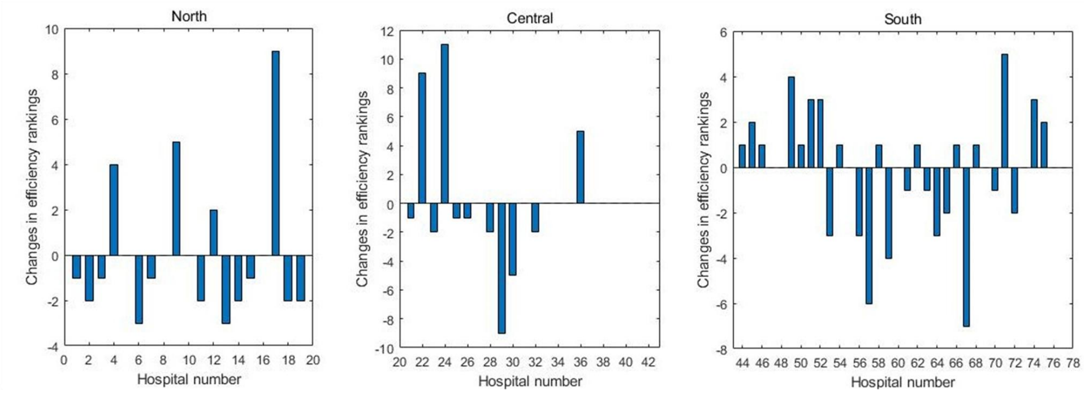

Fig.5 Charges in the efficiency ranking of county-level public general hospitals in Shanxi Province before and after the implementation of quality constraints

STROBE checklist

	Recommendation	page
Title and abstract	Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints: a cross-sectional study Objectives: Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist. Methods: Based on the data from 77 county-level public general hospitals (CPGHs) in Shanxi Province, China, from 2013-2018, we applied the meta-frontier and SBM-undesirable（Slacks-based Measurement-undesirable）DEA(Data Envelopment Analysis) model to measure the CPGHs' medical service efficiency with or without medical quality constraints and evaluate the effects of the new medical reform to explore the utilization of health resources and look for ways to improve the CPGHs' medical service efficiency. Moreover, we analyze the factors affecting public hospital efficiency based on the FRM model. Results：The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54). Factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income. Conclusion: To improve CPGHs' medical service efficiency, the government should increase investment in the northern region, and hospitals should improve the management level and allocate human resources rationally.	1-2
Introduction		
Background/rationale	Background: 1. In China, county-level hospitals are divided into CPGHs, traditional Chinese medical hospitals, and maternal and child health care hospitals. However, most studies do not subdivide the hospitals by type, and different types of hospitals have different resource allocation and output structures. 2. In China, most studies have not considered the differences in production frontiers due to the different natural, social and economic environments in different regions. However, in other industries, some relevant scholars have added relevant non-expected output indicators for research when evaluating efficiency. 3. Ignoring the constraints of medical quality, which is an unexpected output of DEA, will seriously affect hospital efficiency. However, In China, many studies have not considered the issue of unexpected output. Rationale: 1.This study used the meta-frontier DEA model to evaluate the medical efficiency of CPGHs in different regions and it can solve the problem	4-6

	of technical heterogeneity; 2. This study selected "adverse events" as a medical quality indicator. And used the SBM-undesirable DEA model is to solve the problems related to unexpected outputs categorized as "adverse events".	
Objectives	Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist.	1
Methods		
Study design	a cross-sectional study	1
Setting	The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected	6
Variables	Input variables: doctor、nurse、bed and machine; Desirable output variables: treatment、EP and operations; Undesirable output variables: adverse events	13
Data sources/ measurement	The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected. The data excluded other types of hospitals, such as traditional Chinese medical hospitals, maternal and child health care hospitals and other medical institutions.	6
Results		
Main results	The efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54). Factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income.	1-2
Discussion		
Key results	According to the FRM regression results, it is concluded that the factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income. Shortening the average hospital stay can improve hospital efficiency. In areas with higher per capita disposable income of residents, the service efficiency of county-level public hospitals is higher. And the increase in subsidy has a positive effect on the improvement of hospital service efficiency. In addition, the county population, bed utilization rate and the proportion of health technicians also have significant impacts on hospital service efficiency. The higher the population, the higher the hospital efficiency. Increasing the bed utilization rate and the proportion of health technicians will also promote hospital service efficiency.	25-26
Limitations	This study evaluated the efficiency of county public hospitals in Shanxi	25

	Province and explored the influence of scale on hospital efficiency. It provided a reference for the government and hospitals to reasonably control bed size. However, the study has Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.	
Interpretation	1.The Meta-frontier and SBM-undesirable DEA models effectively solved the problem that the efficiency score of hospitals was not on the same production frontier. 2.Medical quality index was set as an output indicator in this study, which means that the hospitals should not only focus on the number of patients, but also focus on the medical quality. 3.Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.	2-3
Other information		
Funding	This study was supported by the Research and cultivation fund of Hainan Medical College (HYPY2020025) and National Natural Science Foundation of China(72204069).	26

Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints: a cross-sectional study

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Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints: a cross-sectional study

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Abstract

Objectives Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist.

Design We applied the Meta-frontier and SBM-undesirable (Slacks-based Measurement-undesirable) DEA(Data Envelopment Analysis) model to measure the medical service efficiency with or without medical quality constraints of the county-level public general hospitals (CPGHs). The assessment includes four inputs, three desirable outputs, and one undesirable output. We conducted the assessment via Max-DEA V.8.19 software. Moreover, we analyze the factors affecting CPGHs' medical service efficiency based on the FRM model.

Setting A total of 77 sample CPGHs were selected from Shanxi province in China from 2013 to 2018.

Results The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54). Factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income.

Conclusions To improve CPGHs' medical service efficiency, the government should increase investment in the northern region, and hospitals should improve the management level and allocate human resources rationally.

Keywords: County-level Hospital Efficiency, Medical quality, Meta-frontier DEA Model, SBM-Undesirable DEA Model.

Strengths and limitations of this study

- This study introduced the the Meta-frontier and SBM-undesirable DEA models to measure the efficiency of the county-level public general hospitals (CPGHs) in China. This process is advantageous to draw reliable and robust conclusions.
- Medical quality index was set as an output indicator in this study, which means that the hospitals should not only focus on the number of patients, but also focus on the

medical quality.

- Due to data unavailability, we only selected the number of doctors, nurses, beds and machines as the input variable and did not include staff income,which is a crucial input variable.
- Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.

Background

In March 2009, the Chinese government started a new medical reform. Since the implementation of the medical reform, China has made great achievements in expanding medical security services [1,2]. The government has vigorously developed primary medical and health services and strived to improve the fairness of the health service distribution [3]. However, the distribution of health resources in China is still unreasonable, and health resources are scarce [4]. High-quality medical resources are mainly concentrated in cities, leading to a significant medical quality gap between urban and rural hospitals [5-7]. Additionally, patients prefer to choose urban hospitals, which leads to the idleness of rural hospital resources [8]. Health resource waste and shortage issues have seriously restricted the service ability of medical and health institutions and led to low medical efficiency [9]. To solve these problems and improve the quality of medical services, the government has implemented a series of reforms in rural hospitals [1,10]. China's urban and rural medical system is mainly composed of urban tertiary hospitals, urban community hospitals, county-level hospitals and township health centers [11]. Among them, county-level public general hospitals (CPGHs) act as a link between China's urban and rural medical systems, and they are the leaders of rural health institutions [12-14]. Their medical services have a wide range of radiation and cover a large population [9]. However, county-level hospitals also have problems such as shortages of human resources, low levels of medical services and uneven distributions of resources [14-16]. For example, Wu noted that the quality of human resources in primary hospitals is not high and the medical service level is poor [17]. Jay found that the average resource levels of county-level hospitals in western China were lower than those in other regions [18]. Therefore, it is very important to improve the utilization rate of primary health resources and the medical efficiency of county-level hospitals.

In recent years, many scholars have studied the medical efficiency of CPGHs in China. Li measured the medical efficiency of 12 CPGHs in Anhui Province and found that it has declined year by year; additionally, the medical reform effect of CPGHs was not significant [19]. Wang analyzed the medical efficiency of 127 CPGHs in China and found that the efficiency of CPGHs still has considerable room for improvement [20]. Jiang conducted a study of 1105 CPGHs in China and noted that although medical reform has increased the scale of hospitals, it has not improved the medical efficiency of CPGHs [9]. Other scholars' studies have also shown that the medical efficiency of CPGHs has room for improvement [12,21,22]. However, in the evaluation of medical efficiency, researchers are most likely to ignore the indicators of medical quality, which lead to some high efficiency hospitals with low medical quality [23,24]. At present, medical quality indicators such as mortality rate, infection rate and adverse events are often selected as undesirable indicators in hospitals efficiency evaluation [25-27]. In SBM-undesirable DEA model, medical quality indicators can be regarded as undesirable indicators. For example, SBM-undesirable DEA model was used by A. Monzeli to measure the emergency departments , which indicated that the undesirable output can determine the hospitals' efficiency [28].Wei Lu used the SBM-undesirable DEA model to measure 77 county-level medical efficiency in China [29].This model is widely used in the field of medical service efficiency evaluation in recent years.

In this study, we used the SBM-undersinable DEA model to measure the medical efficiency of CPGHs. Moreover, considering the inconsistencies in the internal and external environment of the CPGHs area, traditional DEA model can not capture the heterogeneity among CPGHs in different area. To solve this problem, we introduced the Meta-frontier DEA model [30],which is a mature DEA model to solve heterogeneity, to measure the heterogeneity of CPGHs in different area. Therefore, we combined the Meta-frontier DEA and SBM-undersinable model to measure the efficiency of the CPGHs.

Methods

Data Sources

The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected [31]. The data excluded other types of hospitals, such as traditional Chinese medical hospitals, maternal and child health care hospitals and other medical institutions, so they met the homogeneity requirement of the DEA(Data Envelopment Analysis) method.

Meta-frontier and Group Frontier DEA Models

The meta-frontier DEA model was first proposed by Battese [32]. The meta-frontier refers to the potential technical level of all decision making units (DMUs), and the group frontier refers to the actual technical level of each DMU. The difference between them is the different technology sets to which they refer.

According to the meta-frontier DEA model of Battese [33], we took the unexpected output into account. In this case, the technology set (T^{meta}) includes all technically feasible input-output combinations:

$$T^{meta} = \left\{ \begin{matrix} (x,y,b): x \geq 0, y \geq 0, b \geq 0; \\ x\ can\ produce\ \ (y,b) \end{matrix} \right\} \tag{1}$$

In the above formulation, x is the input vector, y is the expected output vector, and b is the unexpected output vector. That is, to obtain a certain output P^{meta} (y, b), the input (x) must be satisfied under the given technological condition (T^{meta}). The production possibility set (meta-frontier) is as follows:

$$P^{meta}(x) = \{(y,b) : (x,y,b) \in T^{meta}\} \tag{2}$$

Therefore, the technical efficiency function of the meta-frontier from the perspective of the output can be expressed as follows:

$$TE^{meta}(x,y,b) = inf_{\beta}\{\beta > 0 : (y/\beta) \in P^{meta}(y,b)\} \tag{3}$$

According to the different levels of economic development, Shanxi Province is divided into three groups: Northern Shanxi, Central Shanxi and Southern Shanxi *(h=1,* *2, 3)*. The group technology set is:

$$T^h = \{(x_h, y_h, b_h): x_h \geq 0, y_h \geq 0, b_h \geq 0; x_h \rightarrow (y_h, b_h)\}, h = 1,2,3 \quad (4)$$

The production set is as follows:

$$P^h(x_h) = \{(y_h, b_h): (x_h, y_h, b_h) \in T^h\}, h = 1,2,3 \quad (5)$$

The group technical efficiency *(h=1,2,3)* can be expressed as:

$$TE^h(x_h, y_h, b_h) = inf_\beta\{\beta > 0: (y_h/\beta) \in P^h(y_h, b_h)\}, h = 1,2,3 \quad (6)$$

Meta-frontier technology is the envelope curve of the group frontier technology. So:$T^m = \{T^1 \cup T^2 \cup T^3\}$.

Technology Gap Ratio (TGR)

The technology gap ratio [33] can be expressed by the meta-frontier and group technology efficiency functions (The results are shown in Figure 1):

$$TGR^h(x_h, y_h, b_h) = \frac{TE^{meta}(x, y, b)}{TE^h(x_h, y_h, b_h)}, h = 1,2,3 \quad (7)$$

Fig 1 Schematic diagram of common frontier and group frontier

Take R Hospital located in Group3 as an example, then

$$TE^{meta}(R) = \frac{OC}{OA}; TE^h(R) = \frac{OC}{OB}; TGR^h(R) = \frac{TE^{meta}}{TE^h} = \frac{OC/OA}{OC/OB} = \frac{OB}{OA} \quad (8)$$

If the TGR is less than 1 or there are obvious differences between the mean values of TE^{meta} and TE^h, it is necessary to divide the CPGHs into different groups. In contrast, if the TGR is close to 1 or there are no obvious differences between the mean values of TE^{meta} and TE^h, there is no need to divide the CPGHs into different groups.

SBM-undesirable DEA Model

The SBM-undesirable（Slacks-based Measurement-undesirable） DEA model [34] of unexpected output is used to construct the efficiency measurement model under the meta-frontier and group frontier conditions, and the formula is:

$$\rho^* = min\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{S_{i0}^-}{x_{i0}}}{1+\frac{1}{S}\left(\sum_{r=1}^{S_1}\frac{S_r^g}{y_{r0}^g}+\sum_{r=1}^{S_2}\frac{S_r^b}{y_{r0}^b}\right)}$$

Subject to

$$x_0 = X\lambda + S^-$$

$$y_0^g = Y\lambda - S^g$$

$$y_0^b = Y\lambda + S^b$$

$$L \leq e\lambda \leq U$$

$$S^-, S^g, S^b, \lambda \geq 0. \quad (9)$$

In the above formulation, *X*, *Y* and *B* represent the input and output vectors of different CPGHs each year. The meta-frontier represents 77 county regions, and the group frontier represents different groups in the 77 county regions; s^-, s^y and s^b are slack variables related to the input, expected output and unexpected output, respectively; *r* represents the *r*-th DMU; and r^0 represents the DMU to be assessed. The objective function ρ^* decreases with $s_h^-(\forall h)$, $s_r^y(\forall r)$ and $s_r^b(\forall r)$, where $0 < \rho^* \leq 1$.

Because the data are from multiple years, homogeneity for each CPGH and statistical relations should be considered. Therefore, we adopted the global reference model proposed by Pastor and Lovell [35] to calculate the Malmquist index. This model can solve the comparability problem caused by considering different frontiers in efficiency evaluation.

Disease Complexity Adjustment for Discharged Patients

Since the disease complexity varies from hospital to hospital, it is unfair to simply input the approximate number of discharged patients into the input-output index. For example, hospitals with high technology levels are likely to treat patients with complicated conditions, and these hospitals will take more time to treat such a patient than to treat a patient with a mild illness. Hospitals with low technology levels can supply health services to patients with mild illness or light symptoms as a result of their limited technical capacities, and patients with severe illness may prefer directly seeking health services at high-level hospitals. Thus, 1000 patients in hospital-A will all have difficult and complicated diseases, and those in hospital-B will have mild diseases. However, when performing efficiency evaluation research, if a quantity of units 1000 is input without considering the complexity of the disease, it would be unfair to hospitals with high technical levels. However, the RCI index can be used to adjust the numbers of discharged patients according to the average length of stay and bed utilization rate [36]. Given the poor quality of the patient records in county-level hospitals, we select the RCI index, which provides a reference for efficiency evaluation in underdeveloped areas. The specific adjustment methods were as follows:

$$RCI_i = ALoS_i * (OCC_i / OCC_s) \qquad (10)$$

In the above formula, $ALoS_i$ refers to the average length of stay in the *i*-th hospital, OCC_i refers to the bed utilization rate of the *i*-th hospital, and OCC_s refers to the average bed utilization rate of all evaluated hospitals. Therefore, the average length of stay will be adjusted upward for hospitals with higher bed utilization rates than the average. The actual number of discharged patients (P) was adjusted based on the RCI of each hospital, and finally, the number of discharged patients (EP) adjusted according to the RCI index was obtained. The formula is as follows:

$$EP = P * (RCI_i/RCI_s) \quad (11)$$

FRM (Fractional Response Model)

The regression equation is:

$$EFFICIENCY_{it} = \beta_0 + \beta_1 ln\, INCOME_{it} + \beta_2 ln\, POPULATION_{it} + \beta_3$$

$$ln\, SUBIDY_{it} + \beta_4 ln\, DAY_{it} + \beta_5 BEDRATIO_{it} + \beta_6 STAFFRATIO_{it} + \varepsilon_{it} \quad (12)$$

where $EFFICIENCY_{it}$ represents the service efficiency of the hospital i in year t, β_0 is a constant term. $INCOME_{it}$ and $POPULATION_{it}$ represent the per capita disposable income and residents population of the district (county) where the hospital i is located in year t, respectively; $SUBIDY_{it}$, DAY_{it},$BEDRATIO_{it}$and $STAFFRATIO_{it}$ represent the subsidy, average length of hospital stay, hospital bed utilization rate and the proportion of health technicians, respectively. ε_{it} is the error term. This paper uses Stata16.0 software for data processing and regression.

To examine the factors that influence the service efficiency of public hospitals, this paper uses the panel Tobit model with right-side restriction for regression. One of the defects of the Tobit model is that it has a strong dependence on distribution and is sensitive to the problem of heteroscedasticity. If the error term does not follow the normal distribution or has a heteroscedasticity issue, the estimation will be inconsistent [37]. In addition, there are some problems in using the Tobit model to analyze the factors of hospital efficiency [38]. In fact, the hospital efficiency in this paper is a natural consequence of the way DEA is defined, and the hospital efficiency measured according to the Non-oriented EBM model is inherently between 0 and 1, which is not because of the Tobit model that set the efficiency greater than 1 to the value of 1.

Papke and Wooldridge [39] proposed the Fractional Response Model (FRM) in 1996, which overcomes many of the limitations of linear and nonlinear econometric models when studying bounded data. Ramalho et.al. [40] further developed the FRM model. The FRM model is a nonlinear model using the Quasi-Maximum Likelihood Estimation (QMLE). Compared with the Tobit model, the QMLE is asymptotically efficient and consistent because the FRM model does not require distributional or heteroskedasticity assumptions on the DEA score [41]. In addition, the advantages of the FRM model are that it allows a nonlinear relationship between hospital efficiency and its determinants, allows error terms to have autocorrelation, and does not allow the efficiency score to fall outside 0-1, which are in line with the research content of this paper. To this end, this paper uses the Fractional Response Model (FRM) for robustness testing. The specification is:

$$E(y_i|\boldsymbol{x_i}) = G(\boldsymbol{x_i\beta}) \tag{13}$$

where the subscript i represents hospital, $\boldsymbol{x_i}$ are the factors, and $\boldsymbol{\beta}$ is the parameter to be estimated. $G(\eta) = exp(\eta)/[1 + exp(\eta)]$ represents a probability distribution function in the form of Logit whose domain is all real numbers and whose range is (0,1).

Referring to Papke & Wooldridge [39], the log-likelihood equation can be estimated by Quasi maximum likelihood estimation (QMLE):

$$l_i(\boldsymbol{\beta}) = y_i ln\,[G(\boldsymbol{x_i\beta})] + (1-y_i) ln\,[1-G(\boldsymbol{x_i\beta})] \tag{14}$$

Finally, maximize Equation (15) to obtain the value of $\boldsymbol{\beta}$ in Equation (13).

$$\max_{\boldsymbol{\beta}} \sum_{i=1}^{269} l_i(\boldsymbol{\beta}) \quad (15)$$

Patient and public involvement

No patient involved

Results and Analysis

Variable Selection

The variables were selected according to previous empirical research and the literature [7, 9, 12, 19-22]. Input variables usually include labor and capital [42]. In our study, the numbers of registered doctors and registered nurses were used to represent the elements of human resources as input variables. Beds and equipment valued above 10,000 yuan were used as capital elements. The total visits, the number of discharged patients (EP) adjusted by the RCI and the number of operations were used as output variables. At present, all critically ill patients in counties in China go to urban tertiary hospitals, so there are almost no death cases [43]. Therefore, in this study, the number of adverse events was used to replace the unexpected output variable as a quality index [44]. The descriptive statistics of the input-output indicators are shown in Table 1.

Table 1. Descriptive statistics

Input/output	Variable	**Mean**	**Std. Dev.**	Min	Max
Input variables	doctor	95.232	42.017	18	278
	nurse	117.985	71.658	9	390
	bed	250.217	125.748	80	790
	machine	226.736	145.973	35	831

Desirable output variables	treatment	95432.120	58710.450	16351	292534
	EP	9607.892	6610.737	756.4231	32707.7
	operations	1470.729	1189.186	81	7926
Undesirable output variables	adverse events	68.712	38.462	10	200

Note: The sample size in the model was 462

The variables for FRM, the dependent variable is the service efficiency of public hospitals. As for the independent variables, according to the existing literature and the consideration of data availability and sample size, the following six types of factors affecting the service efficiency of county-level public hospitals were selected for analysis, including (1) External factors: per capita disposable income of residents (county-level economic factor), number of usual residents (county-level population factor); (2) Internal factors: financial subsidy income (hospital-level financial factor), the proportion of health technicians (human resource factor), hospital bed utilization rate (equipment implementation factor), average length of hospital stay (service delivery factor). The summary of variables for FRM is shown in Table 2.

Table 2. Summary of variables for FRM

Variable name	Variable	Definition
Hospital service efficiency	*EFFICIENCY*	Service efficiency of each county-level public hospital calculated according to the Non-oriented EBM model
Per capita disposable income (yuan)	*INCOME*	Per capita disposable income of usual residents
Resident population (person)	*POPULATION*	Population of usual residents
Financial subsidy income (ten thousand	*SUBSIDY*	Financial subsidy received by hospitals

yuan)		
Average length of hospital stay	*DAY*	$\frac{\text{Number of days that beds are occupied by dischargers}}{\text{Number of people discharged}}$
Utilization rate hospital bed	*BEDRATIO*	$\frac{\text{Number of days that beds are actually occupied}}{\text{Number of days that beds are available}}$
Proportion of health technicians	*STAFFRATIO*	$\frac{Number\ of\ \text{Inspection Technician and Imaging Technician}}{Number\ of\ employees}$

Test and Analysis of the Technology Gap Ratio (TGR)

Under a quality constraint, a mean value comparison test of the obtained technology gap ratio (TGR) was performed, as shown in Table 3. Assuming that the mean value was 1 and the significance level was 95%, the results showed that the average TGR of each group was less than 1. After performing calculations, from 2013 to 2018, the mean value of the hospital TGR in the southern group was at the highest level, close to 1, reaching 0.93, followed by that of the central group of 0.91, and finally that of the northern group at only 0.63. This result indicated that the southern group was closest to the meta-frontier of technology in county-level public general hospitals, followed by the central group and the northern group. Obviously, both the overall TGR and the regional TGR values were significantly different from the assumed mean value of 1. Therefore, the heterogeneity of the division of public hospitals in Shanxi Province was very obvious, and this finding agreed on the conditions of the DEA meta-frontier model; thus, the meta-frontier model could be suitably applied to analyze the results.

Table 3. Comparative test results of the mean value of the technology gap among county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

Region	Mean TGR	t	P

North	0.62649	-17.2815	0.000
Central	0.907907	-8.9249	0.000
South	0.9328708	-6.9778	0.000
Entire	0.8494894	-15.6809	0.000

After calculating the efficiency of county-level general hospitals in Shanxi Province under meta-frontier and group frontier conditions, the temporal trends of the technology gaps in the north, central and southern regions under the quality constraint were further compared. The results are shown in Figure 2.

Figure 2 shows that the mean value of the TGR in the southern and central regions of Shanxi Province was high, while that in the northern region was the lowest, indicating that the central and southern regions provide better hospital management and medical levels as a whole than did the northern region; additionally, they are closer to the technological frontier. The mean value of the TGR in the central and southern regions fluctuated at a high level and remained in a basically stable state, but the mean value of the TGR in the northern region considerably changed. Except for a slight increase in the mean TGR in 2016, other years experienced a downward trend, which indicated that the medical level in the northern region decreased and that different frontiers influenced the efficiency of county-level public general hospitals in different regions of Shanxi Province.

Time Series Analysis of the Technical Efficiency of Hospitals

Figures 3A and B show the trend of the average comprehensive efficiency of sample hospitals in Shanxi Province and in three major regions from 2013-2018 under the meta-frontier and group frontier, respectively. Taking the meta-frontier in Figure 3A as a reference, the overall average medical service efficiency of county-level public general hospitals was more than 0.6, and the medical service efficiency in each region was relatively stable each year; notably, the efficiency in the northern region displayed a slow downward trend. Referring to Figure 3B, the overall average efficiency for the group frontier was approximately 0.75, the southern region was relatively stable, and the trends in the northern and central regions involved inverted U-shaped curves in the early stage; however, all the regions experienced a significant increase in 2018.

Figures 3C and D show the trend of the average comprehensive efficiency of the sample hospitals in Shanxi Province and in three major regions under the meta-frontier and the group frontier conditions, respectively, based on the quality constraints from 2013 to 2018. Taking the common frontier in Figure 3C as a reference, the overall average medical service efficiency of county-level public general hospitals was approximately 0.63, and the medical service efficiency trend in various regions displayed an inverted U-shaped curve in each year; that is, it fluctuated and rose from 2013 to 2016 and then dropped rapidly after 2016. Regarding Figure 3D, the overall average efficiency under the group frontier was approximately 0.75, and the medical service efficiency trend in the northern region displayed a U-shaped curve that fluctuated and decreased from 2013 to 2016 and then rose slowly after 2016. Moreover, the efficiency trends in the central and southern regions were the same as those for the meta-frontier.

Analysis of the Differences in Hospital Technical Efficiency

The distribution of the service efficiency of public general hospitals in Shanxi Province is shown in Figure 4. Graph A shows the distribution of hospital efficiency without quality constraints, and graph B presents the distribution of hospital efficiency under quality constraints. In terms of location, the peak position of the distribution curve in Figure 4B moves to the right compared with that in Figure 4A, indicating an overall efficiency improvement. The kurtosis of the distribution curve for the central and southern regions in Figure 4B is greater than that in Figure 4A, indicating that the distribution of the efficiency was more concentrated in B. The northern distribution curve in Figure 4B displays an obvious bimodal state, indicating that the efficiency distribution was somewhat scattered. Therefore, quality constraints were very important in the hospital efficiency evaluation. A lack of quality constraints would lead to certain deviations in the evaluation results, and the results would not comprehensively reflect the actual operation status of the medical system.

An analysis of the hospital efficiency distribution in Figure 4B was performed. First, for the location, the distribution curves of the hospital efficiency density in the northern, southern and central regions sequentially moved to the right. The distribution curves of the southern and central regions were closely interlaced, indicating that the hospital efficiency levels in the southern and central regions are similar and significantly higher than the level in the northern region.

Second, the distribution curve of the efficiency density in northern hospitals peaks, and the distribution curves of the efficiency density for the central and southern hospitals displays broad kurtosis.

Finally, in terms of shape, the distribution curve of the efficiency density for northern hospitals is bimodal, and those for the central and southern hospitals are unimodal, suggesting that most hospitals in the central and southern regions have little difference in medical level, while the medical level of northern hospitals is polarized; this relation reflects the concept of "the strong get stronger, and the weak get weaker" (Matthew's effect).

Analysis of the Changes in Hospital Technical Efficiency Rankings

To show the changes in efficiency among the sample hospitals before and after the implementation of quality constraints, the comprehensive efficiency values of sample hospitals under the two constraint conditions were ranked, and the changes in hospital rankings were compared. The results are shown in Figure 5. In the northern region, the ranking of hospital 17 increased the fastest, and the rankings of hospitals 6 and 13 decreased most obviously. In the central region, the ranking of hospital 24 increased the fastest, and the ranking of hospital 29 decreased the most. In the southern region, the ranking of hospital 71 increased the fastest, and the ranking of hospital 67 decreased the most.

By analyzing the unexpected outputs of adverse events at hospitals, it was found that the changes in efficiency rankings were related to the unexpected outputs of adverse events; notably, the efficiency ranking increased when the unexpected output level was low, and the ranking decreased when the unexpected output level was high. For example, the average unexpected output of hospitals in the northern region was -14.35, and that of hospital 17, with a medical quality higher than that of most hospitals, was -3.38. However, the average unexpected outputs of hospitals 6 and 13 were -23.78

and -31.08, respectively, and the corresponding medical quality was lower than that of other hospitals. Additionally, the average unexpected output values of hospitals in the central and southern regions were -15.3 and -19.22, respectively, and the average unexpected output values of hospitals 24 and 71 were only -3.09 and -3.49, respectively. Moreover, the average unexpected output values of hospitals 29 and 67 were -23.99 and -57.25, respectively.

The Spearman rank correlation test was used to determine whether there was a correlation between the hospital efficiency values under the two different constraints. The significance level was 1%. The results showed that there was a positive correlation between the efficiency values of sample hospitals under the two constraints. According to the results, the three regions were different: the southern region had the highest similarity, with a correlation coefficient of 0.9673, and the greatest difference was observed in the northern region, with a correlation coefficient of 0.8452.

Analysis of factors affecting public hospital efficiency

The result on factors affecting public hospital efficiency based on the FRM model is shown in Table 4.

Table 4. Regression result of the FRM model

	(1)FRM-Logit	(2)FRM-Logit
Constant	-63.1201 (57.5153)	174.6323** (69.2530)
ln *INCOME*	23.9425*** (8.0147)	57.9482*** (9.1432)
ln *POPULATION*	11.7407** (4.8335)	18.0447*** (4.9030)
ln *SUBSIDY*	18.2966*** (2.1988)	13.6022*** (2.1659)
ln *DAY*	-53.1396*** (8.9505)	-53.4437*** (8.9724)
BEDRATIO	1.8526*** (0.1080)	1.8717*** (0.1104)
STAFFRATIO	4.3761*** (1.1724)	3.9982*** (1.1333)

Wald test	570.78(0.0000)	758.54(0.0000)
Time fixed effect	No	Yes
County fixed effect	No	Yes
Hospital category effect	No	Yes
Observations	1430	1430

Note: The data in parentheses after each coefficient is the standard deviation. To facilitate comparison with the Tobit model, both coefficients and standard deviation are multiplied by 100. In the Wald test, the values on the left side of the parentheses are the values of χ^2 distribution, and the values in the parentheses are the corresponding P values. ***, **, and * represent 1%, 5%, and 10% significance level, respectively.

We can find that the coefficient of per capita income is positive and significant, that is, the improvement of residents' per capita disposable income can improve the service efficiency of county public hospitals; Population factor negatively impacts public hospital efficiency when the fixed effects are not controlled. After controlling for the fixed effects, the coefficient is significantly positive, that is, the resident population in the county where the hospital is located is positively correlated with the service efficiency of county public hospitals; The effect of financial subsidy income on the service efficiency of county public hospitals is significantly positive; The coefficient for the average length of hospital stay is the largest and significantly negative; And the proportion of health technicians has a significant positive impact on the service efficiency of public hospitals.

Discussion

This paper used the meta-frontier model and SBM-undesirable (Slacks-based Measurement-undesirable) model to calculate the efficiency of county-level public hospitals in Shanxi Province from 2013 to 2018. Then, we evaluated the reform effect and resource utilization rate of county hospitals and explored the influence of medical quality on hospital efficiency. Moreover, we analyze the factors affecting public hospital efficiency based on the FRM model.

The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). In other studies, the average efficiency of county hospitals in Chongqing was 0.83 [12], in Anhui Province was 0.956 [19], and in China, as a mean value, was 0.7 [20], suggesting that the efficiency of county-level hospitals in Shanxi Province is obviously low; additionally, the utilization rate of existing resources is relatively low, and the technology used in inefficient. To improve the efficiency level of county-level hospitals, in addition to increasing investments to alleviate resource shortages, it is necessary to improve the utilization efficiency of resources, such as improving hospital management, rationally allocating human resources, and optimizing capital investments [45].

The results showed that the efficiency of county-level public hospitals in Shanxi Province did not improve and even declined in some areas from 2013 to 2018 (Figure 2C). Although the reform of county-level hospitals was initiated in 2012, the effect was not remarkable, as also noted by Jiang et al. [9]. Moreover, the study found that there were regional differences in the efficiency of county-level public hospitals in Shanxi Province. The efficiency level of county-level public hospitals in the central and southern regions of Shanxi Province was high, while the efficiency level in the northern region was comparatively low (Figure 2A and Figure 2C); these trends were also reflected by the technology gap ratio distribution in each region (Figure 1), which indicated that the county-level hospitals in the northern region were far from the technological frontier. Therefore, increasing the resource inputs for hospitals in the northern region of the province should be prioritized to improve their medical levels. Additionally, the population and economic level in northern Shanxi Province are lower than those in the central and southern regions [46]; thus, hospital efficiency may be related to the economic environment and population.

This study also showed that quality constraints had an important impact on hospital efficiency evaluation (Figures 3 and 4). Neglecting medical quality output could lead to underestimates of the hospital efficiency level. This finding could potentially be attributed to the fact that medical quality is often related to hospital management and human resources [47]. With improvements in hospital management and medical treatment ability, medical quality will also increase, as will the corresponding hospital efficiency. Improving the quality of medical services is often the goal of public hospitals [48], but many hospitals begin to expand blindly, resulting in inefficiency [20,41,49]. Pang [50] et al. noted that improperly scaled expansion can lead to technical efficiency in the short term but not in the long term. Therefore, to improve the medical quality level, increasing the technological capacity and improving management are steps.

For the factors that influence public hospital efficiency, firstly, when the per capita disposable income of residents is high, people may pay more attention to their health, and have more requirements for the service and technical level of the hospital. Accordingly, health services will be used more rationally. Secondly, the more resident population in the region, the greater the intensity of the demand for medical services, and the hospital will continuously improve its medical service to meet the demand, thus making the hospital service more efficient. The reason for the low level of significance level is that: on the one hand, the resident population is the macro-level data, which has little impact on the efficiency of the micro-level hospital; on the other hand, the mobility of people seeking medical treatment is high, so the population of the area where the hospital is located has limited effect on the efficiency of the local hospital. Thirdly, if the government increases the financial investment in the hospital, it will help the hospital to introduce high-tech equipment and improve the hospital's infrastructure construction capacity, etc. Thus it will prompt the hospital to realize the rational allocation of resources under the guidance of the government's policy of increasing the corresponding investment. As a result, the hospital achieves more efficient health service, improving the efficiency of hospital services. Fourthly, the average length of hospital stay is an important factor affecting the service efficiency of public hospitals, and a longer length of hospital stay will reduce the service efficiency level of the hospital. This may be because a longer length of hospital stay means hospitals are not treating patients in a timely manner or have to deal with more severe cases, making hospital services less efficient. Fifthly, the bed utilization rate reflects the vacant beds in the hospital. The higher the hospital bed utilization rate, the more patients can be provided with hospital-stay services at the same time, thereby increasing the hospital-stay service output and improving the hospital’s service efficiency. Sixthly, for the positive impact of the proportion of health technicians, the reason may be that the higher the proportion of health technicians, the higher the level of medical service, and the further improvement of the service efficiency of the hospital.

Limitations and suggestions for future research

This study evaluated the efficiency of county public hospitals in Shanxi Province and explored the influence of scale on hospital efficiency. It provided a reference for the government and hospitals to reasonably allocate health resources. However, we believe that our research can be improved and extended in a number of directions. First, the study has Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited. Future studies can be conducted and include CPGHs in other provinces, which are divided by region. Second, we did not include the staff salary as the input variable, mainly due to data limitations. However, further analysis focusing on the staff salary variable is also necessary given that we are studying public hospitals' efficiency, the salary paid to employees by the government is an important input indicator for evaluating public hospitals' efficiency.

Conclusion

This showed that after the implementation of county-level public hospital reform, the efficiency level of county-level public hospitals in Shanxi Province did not improve but remained low. Notably, the utilization rate of resources was low, and the reform effect was not obvious. There are differences in the efficiency of county-level hospitals in different regions, with the highest efficiency in the central region, the second-highest level in the southern region and the lowest level in the northern region. To improve the efficiency of hospitals, support to the northern region should be strengthened, hospital management should be improved, and health human resources should be rationally allocated.

The results also indicated that quality factors have a significant impact on hospital efficiency evaluation. The keys to improving the level of medical quality are to improve the proportion of technical personnel and the level of hospital management. The expansion of county-level hospitals should consider the economic level and service area in the region to avoid expansion and blind investment, potentially resulting in wasted resources.

According to the FRM regression results, it is concluded that the factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income. Shortening the average hospital stay can improve hospital efficiency. In areas with higher per capita disposable income of residents, the service efficiency of county-level public hospitals is higher. And the increase in subsidy has a positive effect on the improvement of hospital service efficiency. In addition, the county population, bed utilization rate and the proportion of health technicians also have significant impacts on hospital service efficiency. The higher the population, the higher the hospital efficiency. Increasing the bed utilization rate and the proportion of health technicians will also promote hospital service efficiency. However, only 77 hospitals in one province were selected for this study, so the extrapolation from this study may be limited.

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Authors' contribution

All authors made significant contribution to this study. JL conceptualized the study. WL collected and analyzed the data. BBG wrote the first draft of the manuscript. XJH、HKW and GYZ interpreted the results and revised the manuscript. The final version submitted for publication was read and approved by authors.

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Data Availability Statement

Data are available in a public, open access repository.

i) The data are mainly from the 2013-2018 Shanxi Statistical Yearbook and China Health Statistics Yearbook, Overall 77 CPGHs in Shanxi Province(a province with a population of 37 million in China) were selected.

ii) The data is held in Baidu web disk. (Link: https://pan.baidu.com/s/1OaqcOy0GVwuHJYQXilcMXQ?pwd=0qsf; Extraction code: 0qsf)

iii) There are no reuse conditions for the data.

Ethics approval and consent to participate

As the descriptive research of this study is an analysis of existing data, which does not involve human participants, so there are no ethics approval is required from the Ethics Committee.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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figure legend in the figure

Figure 1

Title: Schematic diagram of common frontier and group frontier

brief explanation:

"Metafrontier" is formed by the efficiency frontier of 77 county-level public general hospitals

Group1,2,3 represents the sample hospitals

Figure 2

Title: The technology gap ratios in northern, central and southern Shanxi Province from 2013 to 2018 under the quality constrain

brief explanation:

According to the North

According to the Central

According to the South

According to the Entire

Figure 3

Title: Efficiency changes of county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

brief explanation:

According to the North

According to the Central

According to the South

According to the Entire

Figure 4

Title: Distribution of the service efficiency of county-level public general hospitals in Shanxi Province:

brief explanation:

According to the North

According to the Central

According to the South

Figure 5

Title: Charges in the efficiency ranking of county-level public general hospitals in Shanxi Province before and after the implementation of quality constraints

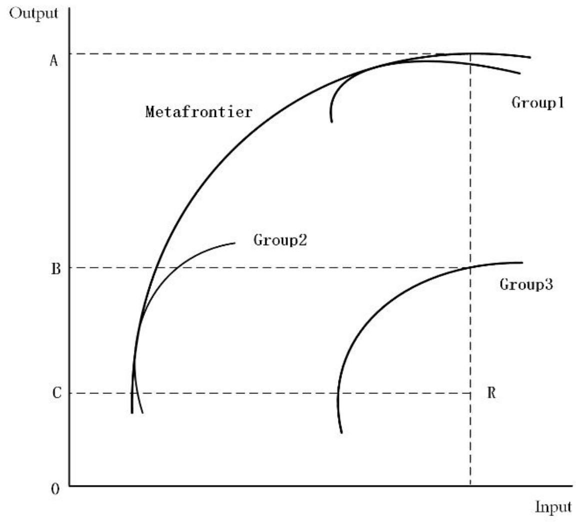

Fig 1 Schematic diagram of common frontier and group frontier

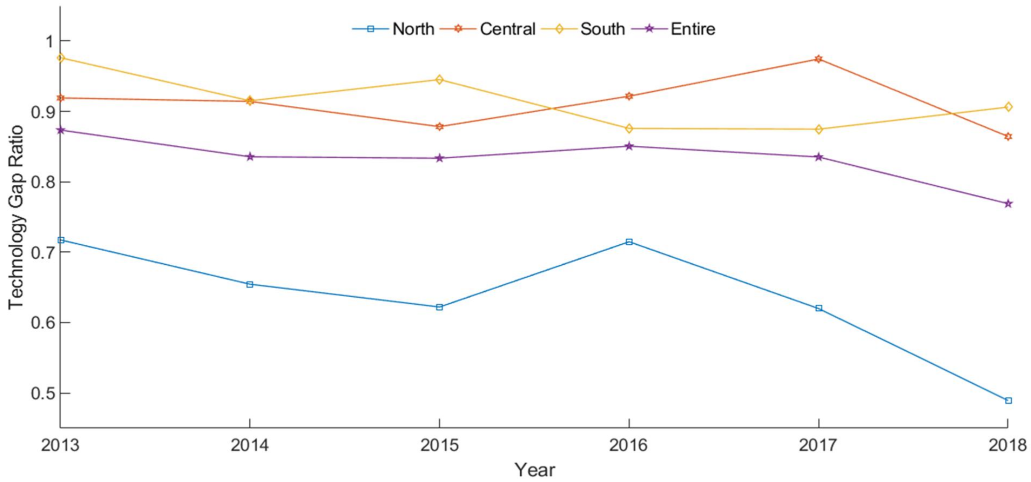

Fig.2 The technology gap ratios in northern, central and southern Shanxi Province from 2013 to 2018 under the quality constraint

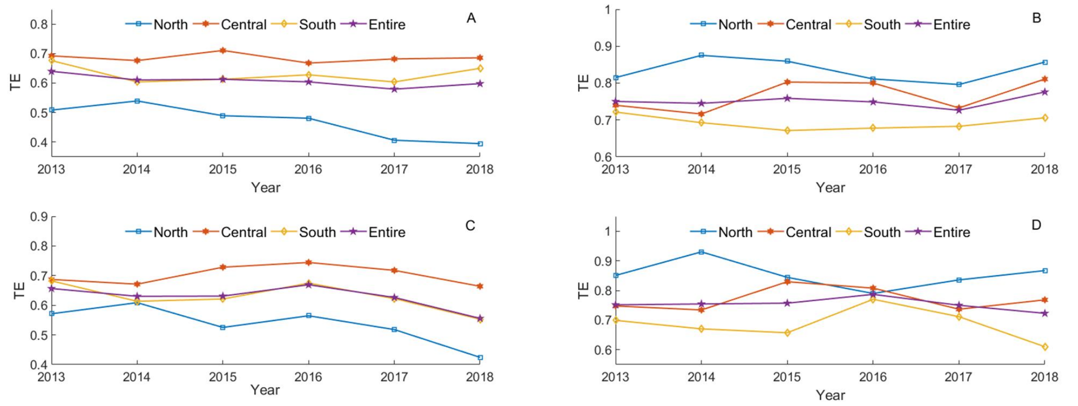

Fig.3 Efficiency changes of county-level public general hospitals in northern, central and southern Shanxi Province from 2013 to 2018

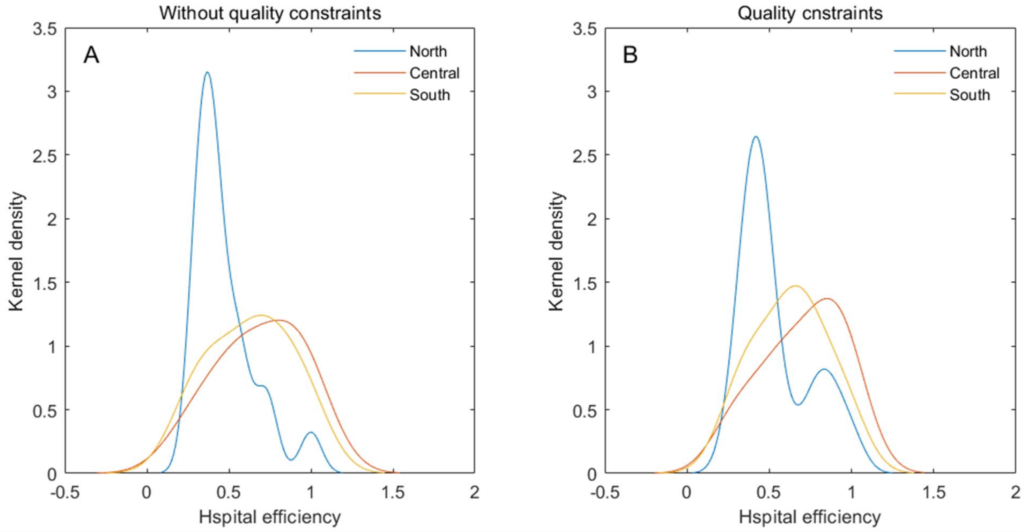

Fig.4 Distribution of the service efficiency of county-level public general hospitals in Shanxi Province

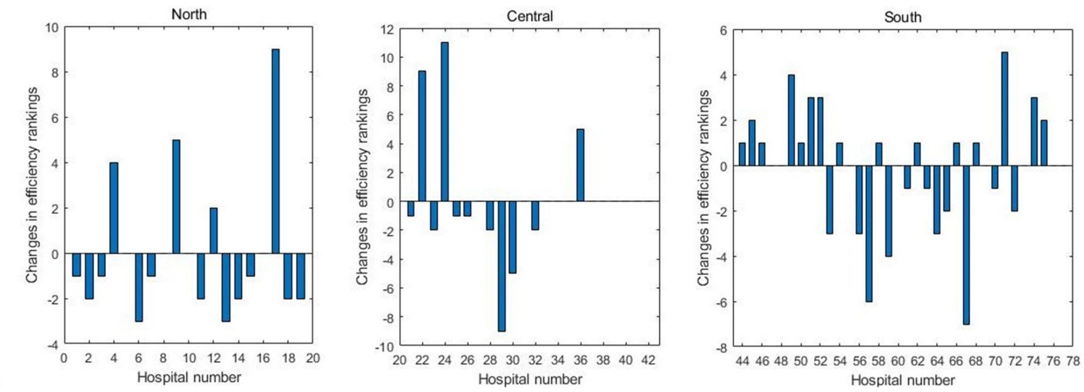

Fig.5 Charges in the efficiency ranking of county-level public general hospitals in Shanxi Province before and after the implementation of quality constraints

STROBE checklist

	Recommendation	page
Title and abstract	Study of the Medical Service Efficiency of County-Level Public General Hospitals Based on Medical Quality Constraints: a cross-sectional study Objectives: Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist. Methods: Based on the data from 77 county-level public general hospitals (CPGHs) in Shanxi Province, China, from 2013-2018, we applied the meta-frontier and SBM-undesirable（Slacks-based Measurement-undesirable）DEA(Data Envelopment Analysis) model to measure the CPGHs' medical service efficiency with or without medical quality constraints and evaluate the effects of the new medical reform to explore the utilization of health resources and look for ways to improve the CPGHs' medical service efficiency. Moreover, we analyze the factors affecting public hospital efficiency based on the FRM model. Results：The results of this study showed that the efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54). Factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income. Conclusion: To improve CPGHs' medical service efficiency, the government should increase investment in the northern region, and hospitals should improve the management level and allocate human resources rationally.	1-2
Introduction		
Background/rationale	Background: 1. In China, county-level hospitals are divided into CPGHs, traditional Chinese medical hospitals, and maternal and child health care hospitals. However, most studies do not subdivide the hospitals by type, and different types of hospitals have different resource allocation and output structures. 2. In China, most studies have not considered the differences in production frontiers due to the different natural, social and economic environments in different regions. However, in other industries, some relevant scholars have added relevant non-expected output indicators for research when evaluating efficiency. 3. Ignoring the constraints of medical quality, which is an unexpected output of DEA, will seriously affect hospital efficiency. However, In China, many studies have not considered the issue of unexpected output. Rationale: 1.This study used the meta-frontier DEA model to evaluate the medical efficiency of CPGHs in different regions and it can solve the problem	4-6

	of technical heterogeneity; 2. This study selected "adverse events" as a medical quality indicator. And used the SBM-undesirable DEA model is to solve the problems related to unexpected outputs categorized as "adverse events".	
Objectives	Since the new medical reform in 2009, county-level hospitals in China have achieved rapid development, but health resource waste and shortage issues still exist.	1
Methods		
Study design	a cross-sectional study	1
Setting	The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected	6
Variables	Input variables: doctor、nurse、bed and machine; Desirable output variables: treatment、EP and operations; Undesirable output variables: adverse events	13
Data sources/ measurement	The data are mainly from the 2013-2018 Shanxi (a province with a population of 37 million in China) Statistical Yearbook and China Health Statistics Yearbook. Overall, 77 CPGHs in Shanxi Province were selected. The data excluded other types of hospitals, such as traditional Chinese medical hospitals, maternal and child health care hospitals and other medical institutions.	6
Results		
Main results	The efficiency level of county-level public hospitals in Shanxi Province is relatively low overall (the mean value of efficiency is 0.61 without quality constraints and 0.63 under quality constraints). This showed that ignoring medical quality constraints will result in lower efficiency and lower health resource utilization for high medical quality hospitals. The medical service efficiency of CPGHs differs greatly among different regions. Under the meta-frontier, the hospitals in the central region had the highest efficiency (efficiency score 0.70), followed by those in the south (efficiency score 0.63), and the hospitals in the north had the lowest efficiency (efficiency score 0.54). Factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income.	1-2
Discussion		
Key results	According to the FRM regression results, it is concluded that the factors that have larger impacts on the service efficiency of county public hospitals are the average length of hospital stay, per capita disposable income and financial subsidy income. Shortening the average hospital stay can improve hospital efficiency. In areas with higher per capita disposable income of residents, the service efficiency of county-level public hospitals is higher. And the increase in subsidy has a positive effect on the improvement of hospital service efficiency. In addition, the county population, bed utilization rate and the proportion of health technicians also have significant impacts on hospital service efficiency. The higher the population, the higher the hospital efficiency. Increasing the bed utilization rate and the proportion of health technicians will also promote hospital service efficiency.	25-26
Limitations	This study evaluated the efficiency of county public hospitals in Shanxi	25

	Province and explored the influence of scale on hospital efficiency. It provided a reference for the government and hospitals to reasonably control bed size. However, the study has Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.	
Interpretation	1.The Meta-frontier and SBM-undesirable DEA models effectively solved the problem that the efficiency score of hospitals was not on the same production frontier. 2.Medical quality index was set as an output indicator in this study, which means that the hospitals should not only focus on the number of patients, but also focus on the medical quality. 3.Only 77 hospitals were chosen in one province, so the extrapolation of this study may be limited.	2-3
Other information		
Funding	This study was supported by the Research and cultivation fund of Hainan Medical College (HYPY2020025) and National Natural Science Foundation of China(72204069).	26