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Incorporating Exercise Efficiency to Evaluate the Accessibility and Capacity of Medical Resources in Tibet, China

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Abstract: Accessibility and capacity of medical resources are key for the health care and emergency response, while the efficiency of the medical resources is very much limited by hypoxia in Tibet, China. Through introducing exercise efficiency, this study explores the accessibility of township residence to county-ship medical resources in Tibet using weighted mean travel time (WMT), and evaluates the medical capacity accordingly. The results show that: 1) the average travel time of township residence to county-level hospital is around 2 h by motor vehicle in Tibet. More than half of the population can not reach the county-ship hospital within 1 h, 33.24% of the population can not reach within 2 h, and 3.75% of the population can not reach within 6 h. 2) When considering the catchment of the medical resources and the population size, the WMT of the county-ship medical resources ranges from 0.25 h to 10.92 h. 3) After adjusted by travel time and exercise efficiency, the county-ship medical capacity became more unequal, with 38 out of 74 counties could not meet the national guideline of 1.8 medical beds per 1000. 4) In total, there are 17 counties with good WMT and sufficient medical resources, while 13 counties having very high WMT and low capacity of medical resources in Tibet. In the end, suggestions on medical resources relocation and to improve the capacity are provided. This study provides a method to incorporate exercise efficiency to access the accessibility and evaluate medical capacity that can be applied in high altitude ranges.

Keywords: exercise efficiency; medical resources; medical capacity; Tibet

1 Introduction

Accessibility and capacity of medical resources are two foundations for population health promotion and protection. The United Nationals Sustainable Development Goal three requires accessibility to health care service for all to achieving universal health care coverage, and sufficient medical capacity can insure the inclusiveness, in particular for emergency preparedness and response like COVID19 pandemic (United Nations, 2015; Wang et al., 2021; Weiland et al., 2021). The medical resources in China, though improved significantly in the past two decades, are characterized by inequality and low efficiency, represented by extreme rich in resources in the east mega regions and thus leading to resources waste, and extreme poor both in high quality medical re-

sources and medical care capacity in many regions in the west (Zhou and Yuan, 2018). The China National Medical and Health Service System Planning Outline (2015–2020) defined the medical resources allocation guidelines for whole China based on the administrative divisions, mainly including the sufficient medical facility and personnel, and reasonable allocation to prevent regional inequity (The State Council of the People's Republic of China, 2015).

In the Tibet Plateau, population is sparsely located with hypoxia caused by high altitude, thus the catchment of the medical resources within effective time and the efficiency of the medical resources are very much limited even for native Tibetans, which make the national guideline, mainly for the medical facilities and personnel for per unit population, less likely suitable in Tibet Plateau. In addition, the public health condition is generally low in Tibet, featured with high prevalence of cardiovascular and respiratory disease (Zhou et al., 2019), malignancies (Pingcuo et al., 2019), infectious disease including tuberculosis, hepatitis B (Nima et al., 2020), echinococcosis (Wu et al., 2018) and plague risks (Zhaxi et al., 2019), and mountain sickness and other chronic endemic caused by unique geo-environment (Li et al., 2021). What is more, the increasing tourist population in Tibet, more than 400 million in the year 2019, make the medical resources more challenging as the non-native population occupy quite some proportion of the medical resources due to trauma or altitude sickness (Gu et al., 2020). All of the above requires optimized medical resources with high efficiency and high capacity.

Effectively characterizing travel time can assist in identifying regions that are beyond the catchment of medical resources (within certain time) and provide guidelines for medical resource optimization. Large amount of related research has been conducted for medical care accessibility evaluation (Murad, 2014; Cheng et al., 2016; Stessens et al., 2017; Choi et al., 2021). Others included elevation as adjustment factor during the accessibility evaluation (Weiss et al., 2018; 2020; Falchetta et al., 2020). Devaraj and Patel (2018) illustrated that because of physical and physiological challenges in high altitude, the efficiency of medical resources is significantly negatively associated with elevation. Research on the medical resources efficiency restricted by hypoxia, either in-situ or simulated hypoxia environment, exclusively exists in sport/exercise medi-

cine or occupational physiology related studies, mainly to evaluate the physical workload or exercise capacity under hypoxia environment, and thus to provide health guidelines for people working in high altitude or for athlete (Wehrlin and Hallén, 2006; Bradwell et al., 2018; Li et al., 2020; Zhang et al., 2020). Therefore, embedding the impact of hypoxia on the efficiency of medical resources in the accessibility analysis can provide more scientific guidelines for medical care allocation in regions with hypoxia.

2 Literature Review

Measurements used for accessibility are mainly travel time, distance or frequency, and the access destinations are mainly medical care (facility or staff), green space, shops, etc. (Sadler et al., 2011; Casey et al., 2012; Masters et al., 2013; Tao et al., 2014; Cheng et al., 2016; Stessens et al., 2017). Accessibility related research are featured with three categories. The first category is exploring the connectivity between the spatial accessibility to medical care or resources and health outcomes. For example, using enhanced 2-step floating catchment area method, Wan et al. (2012) found that spatial access to oncologists is negatively relate to the colorectal cancer survival in rural Texas while not in urban settings. Feng et al. (2019) found that the HIV incidences among the heroin users can be effectively reduced if they are within the 1.5 km coverage of medical facilities in Kaohsiung (Gaoxiong). A study conducted in eastern France indicated that low spatial access to urban physical activity facilities and to general food outlet could lead to a higher likelihood of being overweight for blue-collar worker's children (Casey et al., 2012). For this category, accessibility is used as influencing factor for specific health outcome, such as morbidity, mortality or mental problem.

The second category is related to methodology and innovation. Methods on accessibility have been established extensively through either raster-based or vector-based approach. Raster-based technique summarizes the cost of each grid and gets the shortest path with the lowest cost, represented by weighted mean travel time, two steps floating catchment area method (2SFCA) and related improved methods (Fransen et al., 2015; Tao and Cheng, 2016; Wang, 2016; Luo et al., 2018; Li et al., 2019). Among these, 2SFCA considers the accessibility

to be mediated by not only the distance decay but also the interactions between supply and demand within fixed catchment (Wang, 2016). Travel time calculation is extensively used in regions where connect information is incomplete and measures accessibility largely in terms of the proximity (Chen et al., 2017; Falchetta et al., 2020). Normally, roads data has to be converted into a raster, and land surface conditions can be included as adjustment factor, such as slope, altitude, land use type, *etc*. (Weiss et al., 2018;2020; Huang et al., 2020). Vector-based routing uses road network data, mainly a series of line segments and connecting nodes, to calculate travel costs (time or distance) between two points, represented by proximity analysis, network analysis and its extended methods, such as potential models and spatial interaction models (Song et al., 2010; Tansley et al., 2015; Murad, 2018; Reshadat et al., 2019). Network analysis requests a thorough connectivity between start and end points, and can include the impact of each node and impedance factors. The selection of the methodology mainly depends on the desired precision, scale and data quality. A combination of the raster and vector approaches has also been attempted to enhance the accuracy of accessibility (Jiang et al., 2010).

The third category of accessibility related research assesses the role of accessibility in supporting optimal planning, and mapping disparities in access to care (De Pietri et al., 2013; Cheng et al., 2016; Weiss et al., 2018; 2020;Falchetta et al., 2020; Choi et al., 2021). Most of the studies apply the method or extended method (the second category) for accessibility evaluation as a whole (Meyer, 2012; Munoz and Källestål, 2012; Chen et al., 2014; Cheng et al., 2016; Murad, 2018). Predominant studies conducted by Weiss et al. (2018; 2020) calculated the travel time to health care facilities and to cities,

with the innovation of including slope angle and elevation factors, and for the first time, provided 1 km × 1 km gridded global travel time maps. Based on the United Nations' population projection, Falchetta et al. (2020) established a Geographic Information System (GIS) optimization algorithm based on the least-travel-cost theory, and identified the future optimal allocation of new health care facilities to ensure the universal health care services in sub-Saharan Africa. Inequality with stratifications of region (urban or rural settings) (Vadrevu and Kanjilal, 2016), gender (Reshadat et al., 2019), economic status (Delgado and Canters, 2011), or ethnicity (Wang, 2007) is also considered to identify the vulnerable groups with the approach of accessibility evaluation.

Considering the geographic feature of Tibet and the data quality, we combine the second and the third category in this study. Through incorporating the exercise efficiency, using raster-based approach, an optimized accessibility evaluation method is established, the medical accessibility and capacity in Tibet is evaluated and the medical resource optimization suggestions are provided. The method established here is also applicable for other regions with high altitude globally.

3　Data and Methods

3.1　Research area

Tibet has the highest altitude of 8848 m in Qomolangma Mount, and the average altitude of Tibet is around 4000 m. There were 3.64 million people in Tibet by 2019 and the population density is around 2.96 per km^2 (Tibet Statistical Yearbook, 2020). There are seven prefecture-level cities, 74 counties and 689 towns (Fig. 1a).

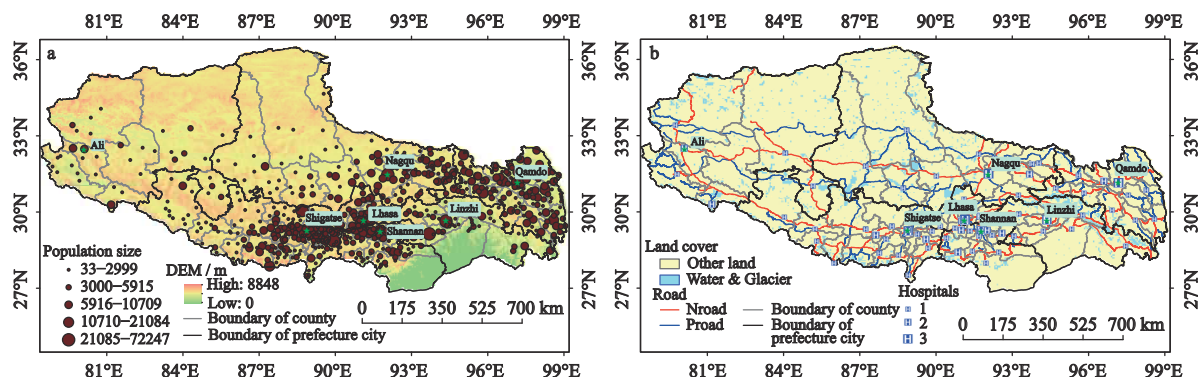The medical care system in Tibet ranges from village level to national level. A village doctor is assigned to

Fig. 1　The population by township (a), road system and hospitals (tier 1–3, b) in Tibet, China

each village and one township medical center for each town, both providing basic medicines and primary healthcare, mainly non-prescription drugs, and drugs that are prescript for specific groups by Center for Disease Control and Prevention (CDC), such as groups with endemic disease or tuberculosis, and coordinate general health promotion, such as plague and hydatid disease prevention education, maternal and child health care, *etc*. Village doctor and township medical center belong to the primary medical care in China, and those in Tibet have low service capacity in particular (The State Council of the People's Republic of China, 2015). At least one tier 1-above hospital is established in each county and many counties have Tibetan Medicine Hospitals, providing special medical services, including life-saving service like surgeries. In 2020 there are 11 (4 are Tibetan Medicine Hospitals) tier 3A hospitals in Tibet located in all of the prefecture-level cities except for Ali (Fig.1b).

The medical insurance system in Tibet is a combination of Urban Workers Medical Insurance, Medical Insurance for Urban and Rural Residents (MIURR) and free treatment for specific cases, including childbirth, infectious diseases, endemic and some major diseases. The first two insurances cover 60%–85% of the cost depending on the level of medical care. In general, the higher the medical care, the lesser the insurance covers. Due to the cost and the distance, outpatient, in particular for rural people, would choose township medical center first, while most of the inpatient would choose county hospital and seldom prefecture-level hospitals, such as tier 3A hospitals (Meng et al., 2016).

3.2 Data
The hospital data including location and number of beds, representing the capacity of the medical resources, are obtained from Regional Statistic Yearbook of Tibet, and the data is for 2018 (http://cnki.nbsti.net/CSYDMirror/area/Yearbook/Single/N2020040364?z=D26). The population data (2018) at town level is obtained from the China National Knowledge Infrastructure (CNKI) socioeconomic bigdata research platform (https://data.cnki.net/NewHome/index). Traffic data, including national road (Nroad), provincial road (Proad) and county road (Croad) of 2018 is from the Resources and Environment Sciences and Data Center of Chinese Academy of Sciences (http://www.resdc.cn/lds.aspx). Town road (Tro-

ad) is retrieved from OpenStreetMap (OSM). Digital elevation model data (DEM, 30 m) and administration map (points and boundary of township, county and province) is from Resources and Environment Sciences and Data Center of Chinese Academy of Sciences (http://www.resdc.cn/lds.aspx). To explore the role of economic development on the capacity and accessibility, GDP, per capita GDP and public budget spending were used, and the data is from CNKI socioeconomic bigdata research platform.

3.3 Methods
3.3.1 *Medical capacity*
Medical capacity is defined as the number of medical beds per 1000 persons. The threshold for bed capacity is defined as 1.8 beds per 1000 persons at county level based on The China National Medical and Health Service System Planning Outline (2015–2020).

3.3.2 *Accessibility*
Weighted mean travel time (WMT) is used to calculate the hospital accessibility. WMT can evaluate the connection between medical resources and population considering both the capacity of the medical resources and the population size. The lower the index, the higher the accessibility. The basic calculation for WMT is as following,

$$L_i = \frac{\sum_{j=1}^{n}(T_{ij} \times H_j)}{\sum_{j=1}^{n} H_j} \tag{1}$$

where L_i is the accessibility of medical resources i; T_{ij} is the travel time of j to i through the shortest path, which is obtained based on the Dijkstra algorithm in GIS (Huang et al., 2020); H_j is the population size of town j.

Considering the hypoxia in Tibet, we introduce exercise efficiency (E_z) to represent the medical care that is restricted both during the medical access and the treatment. Therefore, the travel time (aT_{ij}) is adjusted by the exercise efficiency (E_z) and gradient (P_z) through the following formula,

$$aT_{ij} = T_{ij} \times P_z \times \frac{1}{E_z} \tag{2}$$

And the WMT adjusted by the exercise efficiency can be calculated by the following:

$$AL_i = \frac{\sum_{j=1}^{n}(aT_{ij} \times H_i)}{\sum_{j=1}^{n} H_j} \quad (3)$$

where AL_i is adjusted accessibility; E_z is the adjust factor of exercise efficiency at the height of z during the path searching; n is the number of the towns that each hospital covers based on the shortest distance searching; P_z is the adjusted slope value calculated by the following:

$$P_z = e^{0.005\,556 \times mean_z} \quad (4)$$

where $mean_z$ indicates the mean gradient (m) of cell z and the eight adjacent cells; The 0.005 556 is the reciprocal of the triple Standard Deviation of the $mean_z$ based on distribution pattern the grid values. The larger the P_z, the more difficult to access. To calculate the accessibility, all the elements, including roads, height are gridded. Using Image Analyst function in ArcGIS Pro (with the license from the Institute of Geographic Sciences and Natural resources Research, Chinese Academy of Sciences), the grids are superimposed and calculated. Then using the Cost Distance function in ArcGIS, the accessibility is calculated. In the end, the spatial cluster pattern of access time is analyzed using Spatial Autocorrelation function (Moran's *I* Index).

3.3.3 Speed

Although the availability of travelling method affects individuals' decisions on how to reach the medical resources, according to our previous field investigation funded by the Second Tibetan Plateau Scientific Expedition and Research Program, motorized transport is already quite popular in villages and towns in Tibet. Therefore, we use motor vehicle speed for the travel time calculation (Table 1). The road system in Tibet can be found in Fig.1b. Referring the Regulations for the Implementation of the Road Traffic Safety Law of the People's Republic of China and the traffic restriction

guidelines released by the Public Security Traffic Management Bureau of Tibet (http://www.gov.cn/zhengce/2020-12/27/content_5574617.htm), the speed for the different levels of roads and land cover are listed in Table1. Based on our previous field investigation, for water (mainly rivers) with no township or above traffic system, a pedestrian bridge sometimes exists for access. Therefore, we used Tobler's walking speed of 5 km/h for water system (Tobler, 1993; Huang et al., 2020), though there is overestimation since most of the lakes in Tibet are holy lakes and there is no access either by boat or bridge. For iceberg, it is barely accessible, while in this study, we used the speed of 0.2 km/h, referred from Huang et al. (2020). Indeed, during the travel time calculation, the path searching always bypassed the iceberg due to the extreme high travel time. Based on the speed, we calculated the travel time for different road according to the following formula,

$$T = \frac{10}{V} \times 60 \quad (5)$$

Here, T is time, V is speed, and the speeds for different road and travel time per 10 km is listed in Table 1.

3.3.4 Exercise efficiency factor in high altitude ranges

High altitude can restrict physical and physiological conditions. Studies have explored the restriction of physical activity or exercise capacity under hypoxia environment (Wehrlin and Hallén, 2006; Bradwell et al., 2018; Zhang et al., 2020). Exercise efficiency (E_z) is introduced here to represent the restriction level of high altitude to exercise capacity, where the exercise capacity is restricted by hypoxia and the exercise efficiency is thus reduced. The physiological indicators used to evaluate the restriction mainly including VO_2max (maximal oxygen consumption), Heart rate and SaO_2 (arterial oxygen saturation) (Table 2). Among these, VO_2max is extensively used to assess the exercise efficiency for hypoxia condition (Wehrlin and Hallén, 2006; Bradwell et al., 2018). SaO_2 can turn back to resting level imme-

Table 1 The speed for different road types in Tibet, China

Parameter	Nroad	Proad	Croad	Troad	Oroad	Water	Iceberg
Speed (V) / (km/h)	80	60	40	30	10	5	0.2
Time (T) / (min/10 km)	7.5	10	15	20	60	120	3000

Note: Nroad, national highway; Proad, provincial road; Croad, county road; Troad, town road; Oroad, village road, and other land use types

Table 2 Indicators used for exercise efficiency related to altitude

Indicators (Y)	Main results	Altitude range (X) / m	Ref.
VO$_2$max	VO$_2$max declined linearly with 6.3% decrease per 1 km increasing altitude	300–2800, with 6 gradients	Wehrlin and Hallén, 2006
VO$_2$max	VO$_2$max declined linearly with altitude. $Y=46.949–0.01\times X$ $(P=0.008, R^2=0.929)^*$, after 5 min step test	300–5100, with 5 gradients	Zhang et al., 2020
VO$_2$max	$Y=47.946–0.01\times X (P=0.036, R^2=0.929)^*$, after 5 min step test	300–4550, with 4 gradients	Li et al., 2020
Heart rate	$Y=62.184+0.006\times X (P=0.000, R^2=0.995)^*$, for resting condition	500–5380, with 6 gradients	Wang et al., 2010
SaO$_2$	$Y=98.812–0.004\times X (P=0.099, R^2=0.976)^*$, with medium physical intensity (GB 3869-1997)	450–4100, with 3 gradients	Zhang et al., 1994
SaO$_2$	$Y=98.1–0.003\times X (P=0.031, R^2=0.939)^*$, right after 5 min step test	300–4550, with 4 gradients	Li et al., 2020

Note: *The author established the linear relationship based on the data in respective study

diately after exercise, and comparing to SaO$_2$, ΔSaO$_2$ (after and before exercise) is more suitable for the linear relationship between height and exercise efficiency (Li et al., 2020). Thus, VO$_2$ max is chose as the indicator to represent the exercise efficiency. Based on the articles reviewed, the function of human VO$_2$max change along with altitude is established.

We exclude the Wehrlin and Hallen's result because the altitude range does not fit for Tibet, and use Zhang et al. (2020) and Li et al. (2020)'s results to establish an exercise efficiency (E_z) factor for hospital activity,

$$E_z = \begin{cases} 1 - \dfrac{h-300}{1000} \times 0.1, \ if \ h \geq 300 \ \mathrm{m} \\ 1, \ if \ h < 300 \ \mathrm{m} \end{cases} \quad (6)$$

where E_z is between (0, 1] and h is between 0–8848 m. The medical capacity is influenced by exercise efficiency, and the travel time to the medical resources (driving time) is also influenced by exercise efficiency. Thus, this study uses the adjusted medical capacity and the adjusted access time taking E_z as the correction coefficient, and the lager the E_z, the easier the accessibility.

4 Results

4.1 The spatial distribution of medical resources in Tibet

By 2018, there were 105 hospitals that are higher than fist-class hospital, with 13 463 medical beds in total in Tibet. Among these, 11 are tertiary hospitals and 22 are secondary hospitals. At provincial level, the average allocation of medical beds (including the tertiary and secondary hospitals located in the respective county) is 3.71 per 1000 persons.

At county level, the allocation of medical bed is very

much unequally distributed, ranging from 0.20 to 18.68, with the lowest in Naidong County and the highest in Bayi in Linzhi. In general, counties with higher capacity mainly in the capital of the prefecture city. Chengguan Region in Lhasa, Changdu and Motuo County also have the second highest medical bed capacity of above 11 per 1000 persons. The capacity of medical beds did not meet the national standards of 1.8 per 1000 in 13 counties, accounting for 17.8% of the total (Fig. 2).

Considering the hypoxia caused by high altitude, the efficiency of the medical resources would be impacted, and the capacity of medical beds decrease in general. The efficiency (E_z) for county-ship hospitals ranges from 0.495 of Zhada in Ali to 0.796 of Chayu in Linzhi. At county level, the medical beds capacity adjusted by E_z ranged from 0.13–13.66 per 1000 persons, and 38 counties did not meet the national standards of 1.8 per 1000 persons, accounting for 51.35% of the total.

4.2 The travel time to medical resources

Average speaking, the travel time of resident to county-ship medical resources is 153.32 min, ranging from 0 to 1088 min for Sewu Town of Anduo County in Nagqu Region. There are 131 towns that can get access to the county-ship medical resources within 30 min, covering 1.36 million population, 215 within 1 h covering 1.81 million population, 350 within 2 h covering 2.43 million population, 465 within 3 h covering 2.88 million population, and 637 within 6 h covering 3.5 million population. There are 54 out of the 689 towns can not reach the county-ship medical resources within 6 h, covering 0.14 million population (Fig. 3). In general, there is a reverse relationship between the travel time and the population covered by medical resources ($r = –0.149^{**}$,
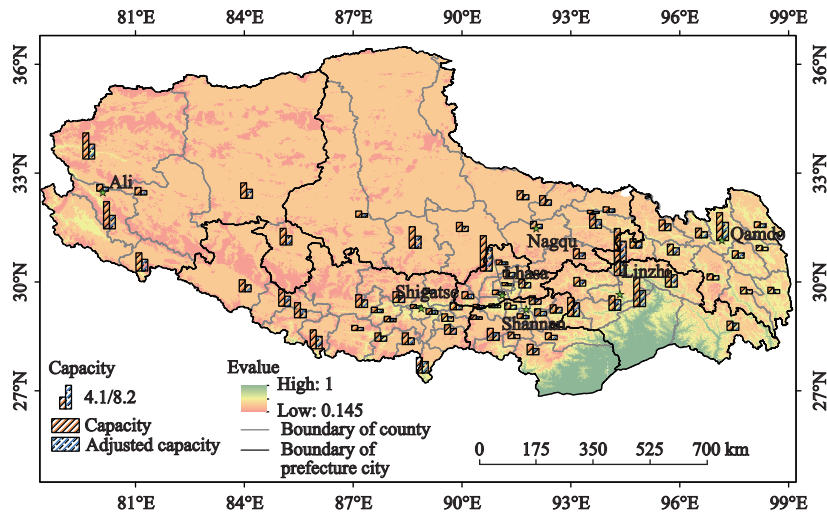
Fig. 2 The medical beds per 1000 at county level (orange stripe: original capacity; blue stripes: capacity adjusted by Evalue (E_z)) in Tibet, China
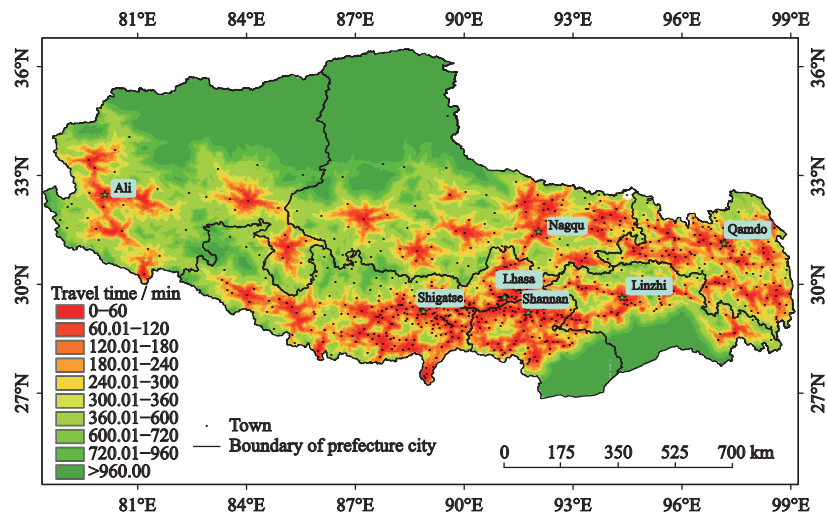

Fig. 3 Travel time from town point to county-ship medical resources in Tibet, China

$P < 0.00$), and the population size covered by travel time show logarithmic function shape, with most people live within the 6 h' catchment of county-ship medical resources (Fig. S1).

The access time of township to county-ship medical resources is unevenly distributed and shows obvious spatial cluster pattern according to Moran's *I* (Fig. 4), with high-high (longer time to access) regions locating in the west, covering 14 counties, and low-low (easy to access) regions locating in Lhasa, Shannan and east part of Shigatse.

4.3 The weighted accessibility and capacity of county-ship medical resources

Fig. 5 shows the weighted mean travel time (WMT) of

the county-ship medical center based on the travel time and the population size covered through shortest access time.

The average county-ship WMT is 2.12 h, ranging from 0.25 h in Chengguan (cgq) of Lhasa and 10.92 h in Shuanghu (shq) of Nagqu. There are 15 counties, mainly surrounding the cities of Lhasa, Shannan, Shigatse and Linzhi, with WMT lower than 1 h. Counties with the highest WMT above 5 h are all located in Ali and Nagqu. For Lhasa and Shanan, all of the counties have WMT less than 2 h. There are 3 out of 7 counties in Linzhi, and 7 out of 18 in Shigatse having WMT higher than 2 h. Only 3 out of 11 counties in Qamdo, 2 out of 11 counties in Nagqu and 1 county in Ali have WMT less than 2 h.
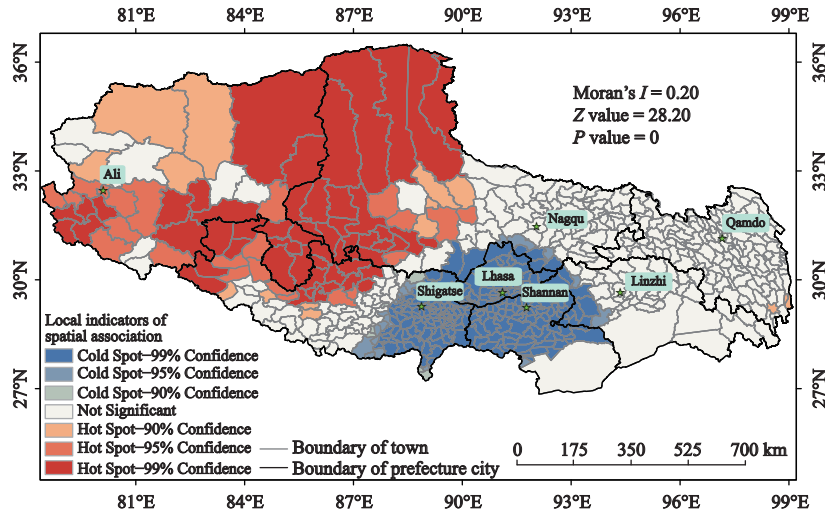
Fig. 4 Spatial pattern of the township travel time to medical resources in Tibet, China. For Moran's *I*, if *Z* value is above 1.65 and *P* is lower than 0.05 or 0.01, the chance that dataset is spatially clustered is high
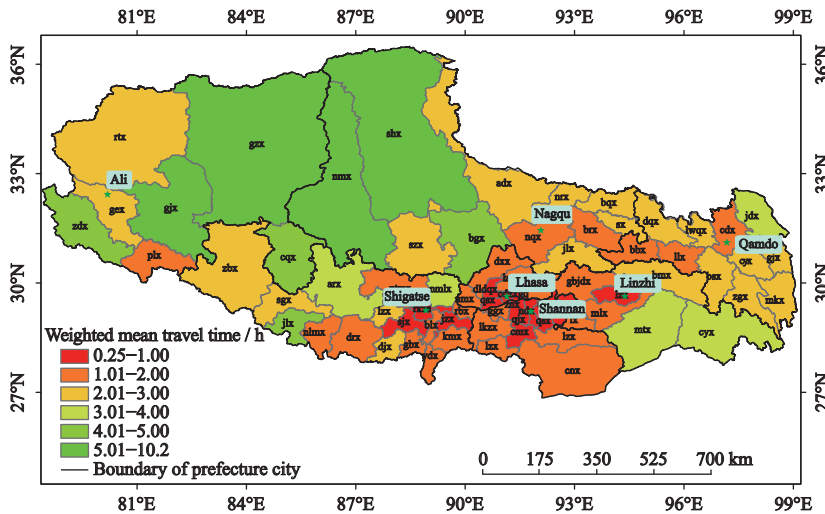

Fig. 5 The weighted mean travel time (WMT) of the county-ship medical resources in Tibet, China. The abbreviations for the county name in this figure can be found in Table S1

Considering there are no barriers in terms of health insurance coverage or culture gap in Tibet between counties, people would choose the hospitals with short journey distance other than the hospitals whining their administrative jurisdiction, and thus the coverage of medical resources will be closer than reality considering the travel distance other than jurisdiction. The towns and population that medical resources of each county covers are calculated based on the shortest access time (Fig. 6 and Fig. S2).

After re-allocating the catchment of the medical resources based on the shortest travel distance, the medical capacity of 29 counties decreased and 38 counties increased comparing with the capacity based on adminis-

trative divisions. Counties with the lowest capacity now are Naidong (ndx) of 0.13 in Shannan, and the highest are Motuo (mtx) of 15.45 in Linzhi. The re-allocation of medical beds based on the travel distance shows the medical beds capacity is even more unequally distributed, with the Std. deviation of the capacity changed from 1.91 to 2.41. The capacity did not change in 7 counties. Among the 29 counties with decreased capacity, 17 counties had bed capacity already below the national guideline and the re-allocation further decreased the capacity. Among the 38 counties with capacity increased, 21 counties having bed allocation already above the national guideline and the re-allocation further increased the capacity. In particular, for Motuo
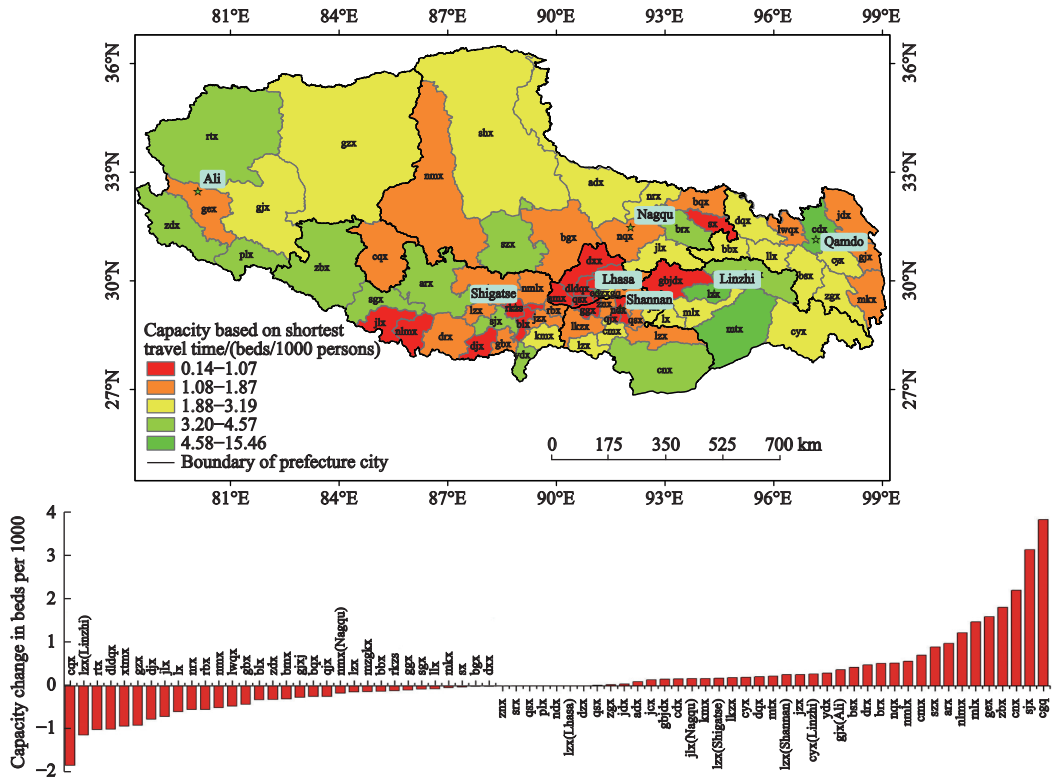
Fig. 6 The medical capacity based on the shortest travel time and the change comparing with the capacity based on administrations. The abbreviations for the county name in this figure can be found in Table S1

(mtx) of Linzhi, the capacity increased from 6.44 to 15.45.

4.4 Overall evaluation of medical resources in Tibet

Based on the WMT and the medical bed capacity adjusted by WMT, counties are clustered into four categories (Fig. 7). The good accessibility of medical resources is defined as 2 h based on the threshold for life-saving ser-

vice access time as suggested by Ouma et al. (2018) and Marsh and Rouhani (2018). The threshold for bed capacity is 1.8 beds per 1000 people based on national guidelines.

There are 17 counties with good accessibility and also adequate medical resources, of which, Chengguan (cgq) in Lhasa, and Linzhi has the highest capacity with
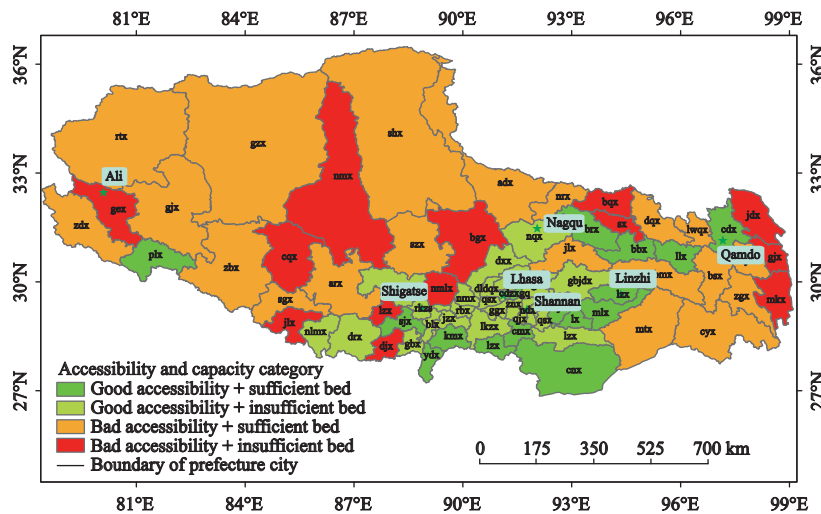

Fig. 7 The evaluated categories based on the accessibility and capacity adjusted by exercise efficiency in Tibet, China. The abbreviations for the county name in this figure can be found in Table S1

WMT less than 1 h. Changdu also has very high capacity while the accessibility is 1.8 h. There are 24 counties having good accessibility but insufficient medical bed, in particular for Rikaze (rkzs), Naidong (ndx), Gongbujiangda (gbjdx), Duilongdeqing (dldqx), Qushui (qsx), Gongga (ggx), Qiongjie (qjx), Linzhou (lzx), and Nielamu (nlmx) with bed capacity lower than 1 per 1000. There are 20 counties with adequate bed while bad accessibility, in particularly for Zhada (zdx), Gaize (gzx), Geji (gjx), and Shuanghu (shx), the WMT are higher than 4 h. Motuo has very high capacity of 15.45 while the WMT is 3.39 h. There are 13 counties having bad accessibility and insufficient beds. Among these, Jilong (jlx), Dingjie (djx) and Suo (sx) have medical bed capacity lower than 1 per 1000, and Bange (bgx), Jilong (jlx), Cuoqin (cqx) and Nima (nmx) have WMT higher than 4 h.

4.5   Correlation analysis
Although the national resources allocation guidelines defined the baseline for medical resources based on the size of the population, the adequacy of medical resources can also be influenced by socioeconomic development and geo-environment (Wan et al., 2021). Exploring these factors can help to optimizing medical resources. However, no significant correlation was found between altitude and medical resources, or with medical capacity (Table 3), indicating the distribution of medical resources did not consider the altitude in Tibet. The size of the population in the region is positively correlated with the medical bed number, which is in line with the national guidelines (The State Council of the People's Republic of China, 2015). Significant correlation was also found between GDP and total bed number, and between per capita GDP and bed capacity, while there is no correlation between public budget spending and medical resources, indicating the size of the local economy instead of the government expenditure are influencing the adequacy of medical resources.

4.6   Method validation
In this study, the travel time between township and county-ship medical centers is calculated via the speed of different roads, land use, and adjusted by exercise efficiency and gradient. Travel time retrieved from Baidu map, which is one of the largest navigations maps in China, is used to validate the travel time calculated in this study. In the end, we selected eight towns using the equipartition method based on the travel time, and the deviation ranges up to 38%, and in general, the shorter travel time, the less deviation (Table 4).

Table 3   The Pearson Correlation analysis in Tibet, China

Variables	Bed number	WMT	Capacity	Capacity by Ez	Capacity by WMT
Altitude	−0.182	0.462**	0.091	−0.058	0.052
Population	0.268*	−0.222	−0.233*	−0.191	−0.203
GDP	0.482**	−0.312**	0.104	0.166	0.070
GDP per capita	0.268*	−0.274*	0.255*	0.317**	0.236*
Public budget spending	0.223	−0.159	−0.132	−0.102	−0.111

Notes: **, significant at 0.01 probability level (2-tailed); *, significant at 0.05 probability level (2-tailed); $n = 74$; WMT, weighted mean travel time; E_z, exercise efficiency

Table 4   Validation of travel time in Tibet, China / min

No.	From town	To hospital	Travel time by current study	Travel time by Baidu map
1	Kangma	Kangma in Shigatse	0	1
2	Liuwu	Duilongdeqing in Lasha	24	28
3	Changlong	Gangba in Shigatse	53	40
4	Mirui	Bayi in Linzhi	98	75
5	Shangchayu	Chayu in Linzhi	143	155
6	Yiri	Leiwuqi in Qamdo	208	176
7	Mindu	Gongjue in Qamdo	299	252
8	Sewu	Anduo in Nagqu	1088	672

5 Discussion and Suggestions

Since the 1950s, the Chinese government started to provide medical support in Tibet, and the medical resources and medical care capacity have experienced significant improvement since 2015, when the 'group-style medical support to Tibet' was introduced by almost all the provinces in the plain areas in China (Fang, 2021). However, the harsh environment and sparsely distributed population make the medical care very difficult to reach timely for everyone. Even though the medical staff can receive some 'plateau subsidy' depending on the level of altitude, the restriction of exercise by hypoxia anyway exists. Currently, the distribution capacity of the medical resources in Tibet is mainly influenced by economy level and population size, but has not consider the restriction of hypoxia in high altitude. This study provides an in-depth evaluation of medical resources in Tibet and assesses the impact of altitude and exercise efficiency on medical care. Inequality exists for both accessibility and capacity of medical resources in Tibet. For accessibility, county-ship medical resources can cover most of the population in Lhasa, Shannan and most Shigatse in a short travel time, while many towns in Ali, Nagqu and north Shigatse are beyond the catchment of the county-ship medical resources. Comparing with 8.9% of the global population that can not reach health care (hospitals and clinics) within 1 h by motorized transport (Weiss et al., 2020), more than half of the population in Tibet can not reach the medical care within 1 h, indicating that the extreme low accessibility to medical resources in Tibet. Although we use county-ship and above hospitals (tier 1−3) and exclude primary medical care (village and township medical centers), the village doctor and township medical center in Tibet have very low level of medical care capacity in general, and can only guarantee the primary health care but not medical care. Our study indicates that 33.24% of the population in Tibet can not reach the life-saving service such as surgery and specialized treatment within 2 h as the threshold suggested by Ouma et al. (2018) and Marsh and Rouhani (2018), much higher comparing with the situation in Sub-saharan Africa (Falchetta et al., 2020). The medical capacity in Tibet is insufficient for many counties, and after adjusted by the exercise efficiency caused by hypoxia, the capacity is even more insufficient with more than half of the counties could not meet the national guidelines. In addition, after considering the travel time and re-allocating the catchment of the medical resources, the county ship medical capacity became more unequal, mainly, the capacity for these counties with lower capacity further decreased and these with higher capacity further increased, indicating that the deployment of the medical resources in Tibet should not only consider the administrative division but also the travel time of the population. Thus we retrieved one general suggestion, that is exercise efficiency in high altitude should be taken into consideration during the distribution of the medical resources. Some specific suggestions are, for these towns with longer (more than 2 h) travel time to hospital, the connectivity of the road system should be improved for one hand, and on the other hand, it is maybe more practical to improve the medical care quality of the township medical centers, mainly increase some life-saving equipment and more importantly, provide emergency response training of the township medical staff, and thus to increase the resilience and emergence response capacity of the township medical care. Second, for these counties with low medical capacity, mainly the counties surrounding Chengguan (Lhasa), Linzhi (Linzhi) and Motuo (Linzhi), it is necessary to redistribute the medical resources to increase the equity. More importantly, for the 13 counties with both low accessibility and low capacity in medical resources, increasing the traffic connectivity and enhance the medical care capacity of township medical centers are suggested, and reasonable medical resources allocation at county level is also in urgent need.

The first highlight of this study is we introduce the exercise efficiency factor that is retrieved based on in-situ human experiment, with altitude ranging up to 5380 m, in the accessibility evaluation. Comparing with the elevation adjustment factor constructed by Weiss et al. (2018), which is based on standard atmosphere calculation, the *Ez* established here directly links with the exercise efficiency caused by hypoxia, and thus can represents the efficiency of the medical resources in a more evidence-based way. The *Ez* established here can also be introduced to some other areas with hypoxia for efficiency study because it covers a very broad altitude range of 300−5380 m. The second highlight is to evaluate the capacity of the medical resources in Tibet combining the medical resources and the catchment according to the shortest distance. Study on the medical re-

sources capacity in China is mainly about the efficiency (technical, scale efficiency) based on the administrative divisions or community levels (Liu et al., 2018; Li and Liu, 2021), though some researchers have proposed the necessity to include spatial distribution and resources capacity for resource allocation (Wu et al., 2020). The idea proposed in current manuscript fit the specific feature of Tibet, that is, the vast territory with sparse population and hypoxia request the necessity to include catchment and efficiency respectively.

The *Ez* value established in this study is based on the human exercise efficiency caused by hypoxia, while we used medical bed number instead of medical personnel to represent the medical resources, which could lead some uncertainties. However, there is a guideline available on the ratio of the number of medical bed to medical personnel for county-ship hospitals in China, with at least 1 to 1.3 (National Health Commission of the People's Republic of China, 2016). The correlation between the two can counteract some of the uncertainties. Second, this study uses the national, provincial, county road and town road for calculating the travel distance, indeed, the traffic system in Tibet is updating very fast nowadays, this might lead to the overestimation of the travel time.

6   Conclusions

In this study we characterize medical resources accessibility and capacity in Tibet and we propose an exercise efficiency factor (in function of altitude), to adjust for medical resources accessibility and optimized capacity. Inequity exists for both the medical resources accessibility and capacity in Tibet. The average travel time of township residence to county-level hospital is around 2 h. Regions with longer travel time are located in the west (mainly in Ali), and regions with shorter travel time are located in Lhasa, Shannan and east part of Shigatse. More than half of the population can not reach the county-ship hospital within 1 h, 33.24% can not reach within 2 h, and 3.75% can not reach within 6 h. For the medical resources capacity, after adjusted by the exercise efficiency, the county-ship medical capacity is even more unequally distributed, with 38 out of 74 counties could not meet the national guideline of 1.8 medical beds per 1000, while some counties have extreme high capacity. There are 13 counties having very low weighted travel time and low capacity of medical

resources. Based on findings above, it is suggested to take exercise efficiency into consideration during the medical resources allocation in high altitude regions, and for the counties with low accessibility and low medical capacity, increasing the traffic connectivity and more importantly, enhancing the medical capacity of township medical centers are very much needed in Tibet.

Supplements

Figs. S1−S2 and Table S1 could be found in the corresponding article at http://egeoscien.neigae.ac.cn/article/2022/6.

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