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Research Article

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Measuring COVID-19 vaccination coverage to support healthcare equity decision-making in urban areas

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Abstract

Background: Limited studies have been conducted on access to COVID-19 vaccines and identifying the most appropriate health centres for performing vaccination in metropolitan areas. This study aimed to measure potential spatial access to COVID-19 vaccination centres in Mashhad, the second-most populous city in Iran.

Methods: The age structure of the urban census tracts was integrated into the enhanced two-step floating catchment area model to improve accuracy. The model was developed based on three different scenarios: only public hospitals, only public healthcare centres, and the top 20% healthcare centres were employed as potential vaccination facilities. The weighted decision-matrix and analytic hierarchy process based on four criteria (i.e. service area, accessibility index, capacity of vaccination centres, and distance to main roads) were used to choose potential vaccination centres with the highest suitability for residents.

Results: Our findings indicate that including the both public hospitals and public healthcare centres can provide high accessibility to vaccination in central parts of the urban areas. However, using only public healthcare centres for vaccination can provide higher accessibility to vaccination sites in the eastern and north-eastern parts of the study area. Therefore, a combination of public hospitals and public healthcare centres is recommended for efficient vaccination coverage.

Conclusions: Measuring spatial access to COVID-19 vaccination centres can provide valuable insights for urban public health decision-makers. Our model, coupled with geographical information systems (GIS), provides more efficient vaccination coverage by identifying the most suitable healthcare centres, which is of special importance when only few centres are available.

Keywords: COVID-19, Spatial accessibility, Spatial inequality, Two-step floating catchment area, Vaccination coverage, Iran.

1-Background

The COVID-19 pandemic has posed substantial costs on individuals and societies, both by direct impact on human physical and mental health, as well as indirectly through economic and social restrictions. Non-pharmaceutical strategies such as social distancing, mask-wearing and economic lockdown are effective control strategies for stop holding up transmission, but notoriously difficult to fully reinforce (1, 2). Amazingly, several effective vaccines could be developed, produced and pass regulatory offices in different countries not much more than a year after the first COVID-19 outbreak in Wuhan, China (3). Indeed, large-scale vaccination is considered the best strategy to address this crisis (4) and so far 12 different vaccines have been endorsed for full or restricted use by the World Health Organization (5), and many countries are now striving to vaccinate their residents to reduce the risk. However, not only is vaccine production lagging demand (5), but access to vaccination centres is a hurdle making vaccine delivery a challenge; thus, careful planning is needed to ensure that everyone has appropriate access to vaccination against this new virus.

Access to healthcare is a question of the degree of effort needed to reach required medical services (6). It has five primary dimensions: availability, accessibility, accommodation, affordability and acceptability (7, 8). While availability refers to the number of available services in the healthcare centres (9), and it is evident that each healthcare facility cannot provide all different services that might be sought, we focussed on accessibility, i.e. the physical distance between healthcare centres and those who might need its services. This is ordinarily given by the length of, and how close it is to, the Euclidean distance (the straight line between source and destination) and must be calculated considering all possible road connections available (10, 11). For example, the drive time from individuals' homes to healthcare centres has also been used in many studies to measure the accessibility dimension (12, 13). As accessibility is related to geographical factors it also labelled spatial access with affordability, accommodation and acceptability considered non-spatial access dimensions, while the availability dimension falls somewhere in-between (14, 15). Another classification categorises access into revealed access and potential access, where the former refers to the actual use of services, while the latter is a proxy of the ability of individuals to use these services (16). In this study, potential spatial access (PSA) to health centres indicates the degree of geographical access to them considering both the geographical distance and the capacity to identify areas characterized by poor access to COVID-19 vaccination centres.

As shown by our research group previously, the two-step floating catchment area (2SFCA) is a robust methodology to measure PSA to healthcare services (17). The method consists of two major steps. First, it calculates the capacity-to-population ratio for each healthcare location. Second, it sums the ratios for residential sites where healthcare locations overlap. However, the 2SFCA approach has drawn sharp criticism for disregarding the differences in accessibility within catchment areas assuming that all humans located within them have equal accessibility (18). To address this issue, the enhanced 2SFCA (E2SFCA) was developed by Lou and Qi (19) and has been further worked out by assigning geographical weights to both steps of the calculation process, which differentiates the travel-time zones through incorporating distance-decay (20).

Limited studies have examined the spatial accessibility of people to COVID-19 vaccination facilities. However, the accessibility for vaccination at a centre proposed as a pilot COVID-19 vaccination programme in Hamilton, Ontario, Canada found that the selected sites did not serve the rural and urban residents appropriately; moreover, the associated cost of travel time was anticipated to be disproportionally borne by lower-income urban populations and rural residents (21). Another study conducted in China compared four optimal vaccine distribution scenarios, including random strategy, age strategy, space strategy as well as space and age strategy finding that 30-40% vaccine coverage was needed to control the epidemic under the space and age strategy, while 60-70% vaccine coverage was required for a random strategy (22).

A study conducted in the city of Warsaw, Poland, measured spatial access to COVID-19 vaccination sites using Thiessen polygons (also known as Voronoi polygons) (23). They identified spatial inequalities and areas with poor access to vaccination sites and proposed activating additional sites either located *ad hoc* or using mobile vaccination sites to achieve uniform vaccination coverage. Importantly, the elderly population was found to be a significant variable in their analysis (23). A study in Florida, USA, evaluated the spatial accessibility to COVID-19 testing sites using the 2SFCA method by integrating both driving and walking modes. Their results suggest that increased efforts are needed to improve accessibility to testing sites among the elderly and those without private vehicles (24). Another Florida study assessed the spatial accessibility of COVID-19 patients to intensive care unit (ICU) beds, using both the 2SFCA and the E2SFCA methods, developed an accessibility ratio difference index to evaluate the difference between the models based on spatial access (25). They found that the 2SFCA method overestimates the accessibility in areas with a lower number of ICU beds due to the "equal access" assumption of the population within the catchment area (CA) (25).

A study in Brazil measured the geographic access to COVID-19 healthcare services using a balanced float catchment area approach and identified substantial social and spatial inequalities in access to health services during the pandemic (26). Their findings moreover indicated that ICU equipment availability varied considerably between cities and was substantially lower among black and poor communities (26). Bauer et al. (26) measured access to ICU beds in 14 European countries using a regional ratio of ICU beds to 100,000 population as the accessibility index and the distance to the closest ICU and arrived at high indices in Germany, Estonia and Austria, with the lowest in Sweden and Denmark. Importantly, the study identified a negative correlation ($r=-0.57$; $p\text{-value}<0.001$) between ICU accessibility and the COVID-19 case fatality ratio (27). Another study, conducted in Melbourne, Australia, identified the most vulnerable areas to COVID-19 based on people ≥65 years old and people living with disabilities by incorporating the travel time from priority areas to palliative medicine and hospital services as estimates of accessibility (28). While a study in Colombia found a high degree of spatial heterogeneity for ICU supplies in the study area by employing the E2SFCA to evaluate available ICU supplies for every thousand inhabitants in the Manizales-Villamaría metropolitan area during the COVID-19 pandemic (29), results based on the same technique in Chicago, USA suggest that southern Chicago needs additional health care resources and that vulnerable populations often resided in areas with too low spatial accessibility (30).

With respect to COVID-19 vaccination, it is vital to prioritise the elderly population as it has been shown that higher age increases the risk of mortality (31). In this study, we measured the PSA to vaccination centres by developing a modified version of the E2SFCA model using a weighted population classified by age structure in each geographical area, as this enhancement should generate more realistic results for healthcare decision-making. A Geographical Information System (GIS)-based approach was used to choose the most appropriate potential healthcare centres for performing COVID-19 vaccination in the urban areas.

2-Methods

2-1- Study area

The study location was the city of Mashhad, capital of Razavi-Khorasan Province in north-eastern Iran. Mashhad is located between latitudes 36°10'and 36°25'N, and longitudes 59°25'and 59°46'E, covering an area of 307 km² (Figure 1). According to the 2016 national census statistics, the city population was almost 3.3 million then and just slightly higher at the time of the study (32). Mashhad consists of 17 municipality regions, 175 districts and 1,301 census tracts (CTs). In this study, we considered the CTs as they provide the finest resolution for accessibility analysis. At the time of conducting this study, there were 26 active public hospitals and 271 public healthcare centres in Mashhad (Figure 1).

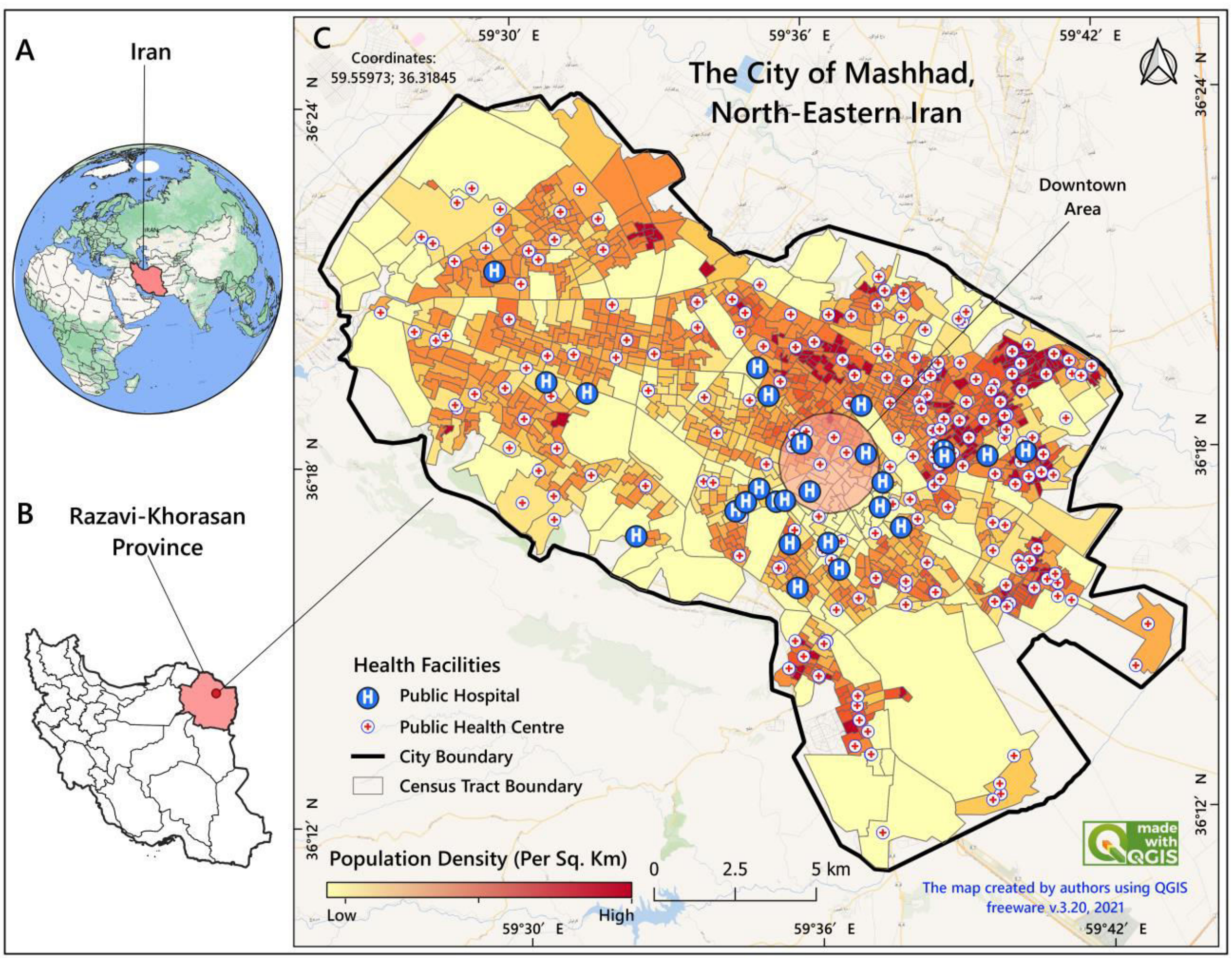

Figure 1 Geographic location of the study area, with distribution of hospitals, public healthcare centres and population density per km2

2-2- Data

Data on the 26 public hospitals and 271 public healthcare centres, including capacity that depends on available equipment and staff, were obtained from Mashhad University of Medical Sciences. Demographic characteristics of all CTs (including population size stratified by age and area) were obtained as a GIS shapefile from the Statistics Centre of Iran (32). The addresses of all healthcare centres and hospitals, city boundary and road network were retrieved from Mashhad Municipality and updated based on the Google Maps (https://www.google.com/maps) and OpenStreetMap (https://www.openstreetmap.org/) websites. All above data are freely available via the link provided in the data availability section.

2-3- Development of the age-integrated E2SFCA

2-3-1- Calculating the weighted population

To measure the PSA to vaccination centres, the age structure of each CT was integrated into the E2SFCA method as an influential factor of COVID-19 mortality. We weighted each age group in the accessibility formula according to Centers for Disease Control and Prevention (CDC), Atlanta, GA, USA (33):

Eq. 1

$$\begin{aligned} &Weighted\ population = \\ &Pop_{0\text{-}4} \times 2 + (Pop_{5\text{-}9} + Pop_{10\text{-}14} + Pop_{15\text{-}19}) \times 1 + (Pop_{20\text{-}24} + Pop_{25\text{-}29}) \times 10 + \\ &(Pop_{30\text{-}34} + Pop_{35\text{-}39}) \times 45 + Pop_{40\text{-}44} + Pop_{45\text{-}49} \times 130 + (Pop_{50\text{-}59} + Pop_{60\text{-}64}) \\ &\times 440 + (Pop_{65\text{-}69} + Pop_{70\text{-}74}) \times 1300 + (Pop_{>75} \times 3200) \end{aligned}$$

where Pop_x denotes population for age group x

2-3-2- Identifying the catchment areas

The CA is the basis of the E2SFCA method (19). According to previous studies (20, 34-36), we defined these areas by radius, i.e. 1 km (CA-1), 1.5 km (CA-2) and 2 km (CA-3), taking into account the average population density of the city (~20,000 people per km^2). The distances chosen are routine minimum and maximum values for defining service areas for health facilities in Iran's major cities (37). Moreover, the speed limit of 30 km/h (based on the average speed when driving a car in the city) was considered the basis of travel-time analysis. The network analysis tools in QGIS software (https://www.qgis.org/en/site/) were used to identify the service areas.

2-3-3- Calculations

In step 1, the CAs were set at 1, 1.5, and 2-km distance to the jth healthcare location. We searched all weighted population locations (k) within the threshold travel-time zone (D_r) from healthcare centre j (CA $_j$). Then, we computed the vaccination capacity-to-weighted population ratio R_j within the CAs using Eq. 2 below following previous studies (11, 24, 41, 42).

Eq. 2

$$R_j = \frac{S_j}{\sum_{k\in\{d_{kj}\in D_r\}} P_k W_r} = \frac{S_j}{\sum_{k\in\{d_{kj}\in D_1\}} P_k W_1 + \sum_{k\in\{d_{kj}\in D_2\}} P_k W_2 + \sum_{k\in\{d_{kj}\in D_3\}} P_k W_3}$$

where P_k is the population of the k^{th} CT falling within the CA j ($d_{kj}\in D_r$); S_j the vaccination capacity at healthcare centre j; d_{kj} the travel time between k and j; and D_r the r^{th} travel time zone ($r\in\{1,2,3\}$) within the CA in question. W_r represents the distance weight for the r^{th} travel-time within the CA calculated by the Gaussian function. The weights set (1.00, 0.68, 0.22) were used to capture the distance decay of access to the j^{th} healthcare centre.

In step 2, we searched all locations j for people in i^{th} CT within the 1, 1.5, and 2-km distance radius. Then, using Eq. 3 below, we summed up the vaccination capacity-to weighted population ratios R_j (calculated in step 1) for all CTs. The same distance weights derived from the Gaussian function were applied in different travel-time zones to account for the distance decay.

Eq. 3

$$A_i^F=\sum_{j\in\{d_{ij}\le D_r\}} R_j W_r=\sum_{j\in\{d_{ij}\le D_1\}} R_j W_1+\sum_{j\in\{d_{ij}\le D_2\}} R_j W_2+\sum_{j\in\{d_{ij}\le D_3\}} R_j W_3$$

where A_i^F represents the accessibility vaccination centre for the population at location i; R_j the vaccination capacity-to-weighted population ratio at healthcare centre j that falls within the CA of population centre i ($d_{kj}\in D_r$); and d_{ij} the travel time between i and j. The E2SFCA calculations were performed under three different scenarios as follows:

<u>Scenario 1: Accessibility to public hospitals (PHs)</u>

In many developing countries, including Iran, PHs act as general and special care facilities and the first point of contact when the patient is referred to specialist care (20). Hospitals are usually well-equipped and can thus be used as public vaccination sites when needed. In this scenario, the PSA to PHs as the potential vaccination centre (PVC) was calculated Considering all 26 active PHs (Figure 1). Since not all hospital staff are qualified to perform vaccinations, only 4% of each hospital's capacity (with an average capacity of 24.85 people as vaccinators) was entered into the accessibility measurement.

<u>Scenario 2: Accessibility to public healthcare centres (PHCs)</u>

The PHCs are the second main health facilities that can be used for public vaccinations during pandemics. In this scenario, 271 PHCs with a capacity of 1 to 5 people (with an average capacity of 2.05 people as vaccinators), were included in the E2SFCA model. The number of PHCs is almost 10 times higher than that of hospitals, and they are well-dispersed across the city. Therefore, the PHCs have a stronger potential when acting as vaccination centres.

<u>Scenario 3: Accessibility to PHs and PHCs</u>

In this scenario, all 26 PHs and all 271 PHCs were entered into the E2SFCA model.

2-4- Choosing the most appropriate centres for vaccination (the proposed model)

Many countries have used available public space for vaccination, e.g., cinemas, shopping malls, even outdoor areas such as football arenas and the like. However, we did not take this possibility into account since our primary aim was to evaluate the capability of the modified version of the E2SFCA model to measure the PSA to available medical centres. Since it is not feasible to equip and prepare any resource for public vaccination, especially in developing countries, PHs and PHCs with high scores based on four main criteria were selected for administering vaccines. These criteria were accessibility index, service capability, distance to main roads and capacity as vaccination centre, described as follows:

2-4-1-Accessibility index

The accessibility index was derived from the calculation of PSA in scenario 3 (Figure 2-A). The accessibility index was classified into five categories depending on the PSA for the following classes of CTs: very high (PSA= 0.000025-0.000037), high (PSA= 0.000017-0.000025), medium (PSA= 0.000011-0.000017), low (PSA= 0000006-0.000011) and very low (PSA= 0-0.000006). The CTs with low PSAs that fell into the very high category were considered as the highest priority for improved accessibility to vaccination. Therefore, higher weights were assigned to healthcare centres in CTs with low PSAs. The weighting was employed to enhance the access to the nearest healthcare centre for people in deprived areas.

2-4-2-Service areas

Equitable accessibility requires optimum allocation of health facilities (38). However, these areas do not have uniform geometric shapes, so the QGIS version of hexagonal tessellation was applied to achieve more homogeneous and geometrically defined service areas for the healthcare centres (depending on the area and population density of the city). The city was therefore divided into 50 equal 1,000-ha hexagons (Figure 2-B). The radius of these theoretical service areas was set at 2 km, i.e. the maximum standard service area (coverage) for access to a health facility (39). Then, the available PVCs closest to the geometric centres of these hexagons were given higher weights and consequently selected as centres with comparatively high suitability as vaccination sites.

2-4-3- Distance to main roads

Travel time and distance from the location of residents to health or medical facilities are the foundation when calculations are carried out to find locations with high accessibility (40). In other words, medical facilities located at a convenient distance from main roads decrease travel time to the vaccination services. In contrast, larger distances to healthcare facilities (that translates into longer travel times) obstruct visits and revisits. There is no universally accepted superior relation between medical care facilities and the range of roads to reach it. According to Silalahi et al. (41), more attention should be paid to the transport network for easy access to PVCs. In this study, distances of 100 m (very desirable), 150 m (desirable), and 200 m (somewhat desirable) from the main roads were defined as one of the sets of criteria for selecting PVCs when applying buffer analysis in QGIS. The PVCs within the distance buffers were then assigned weights, and the PVCs outside these buffer zones with no access to main roads (especially for public transport users) were excluded from the analysis (Fig. 2-C).

2-4-4- Vaccination centre capacity

In this study, PHs and then PHCs were ranked according to their capacity, so that centres with higher capacities were given a higher chance of selection. At the same time, the centres without proper facilities and equipment (e.g., centres with two vaccinators or less) were not given priority status (Fig. 2-D).

The weighted decision-matrix method proposed by Stuart Pugh (42), practical both for simple and complex decisions (43), was used to select the most appropriate centres. First, a 297*4 matrix was formed. Then, each criterion was normalized through numbers between 0 and 1. According to the difference in importance of each main criterion, the weights were calculated using the Analytical Hierarchy Process (AHP) (44) based on the opinions of 10 health professionals. Afterwards, the obtained weights from the main indices were multiplied by the corresponding numbers to arrive at the actual values of the selected criteria. For each potential vaccination centre, the obtained number from this calculation gave the final score that was finally used to rank the PVCs. The top 20% of the centres, i.e. those with the highest capabilities for vaccination according to the final scores, were selected.

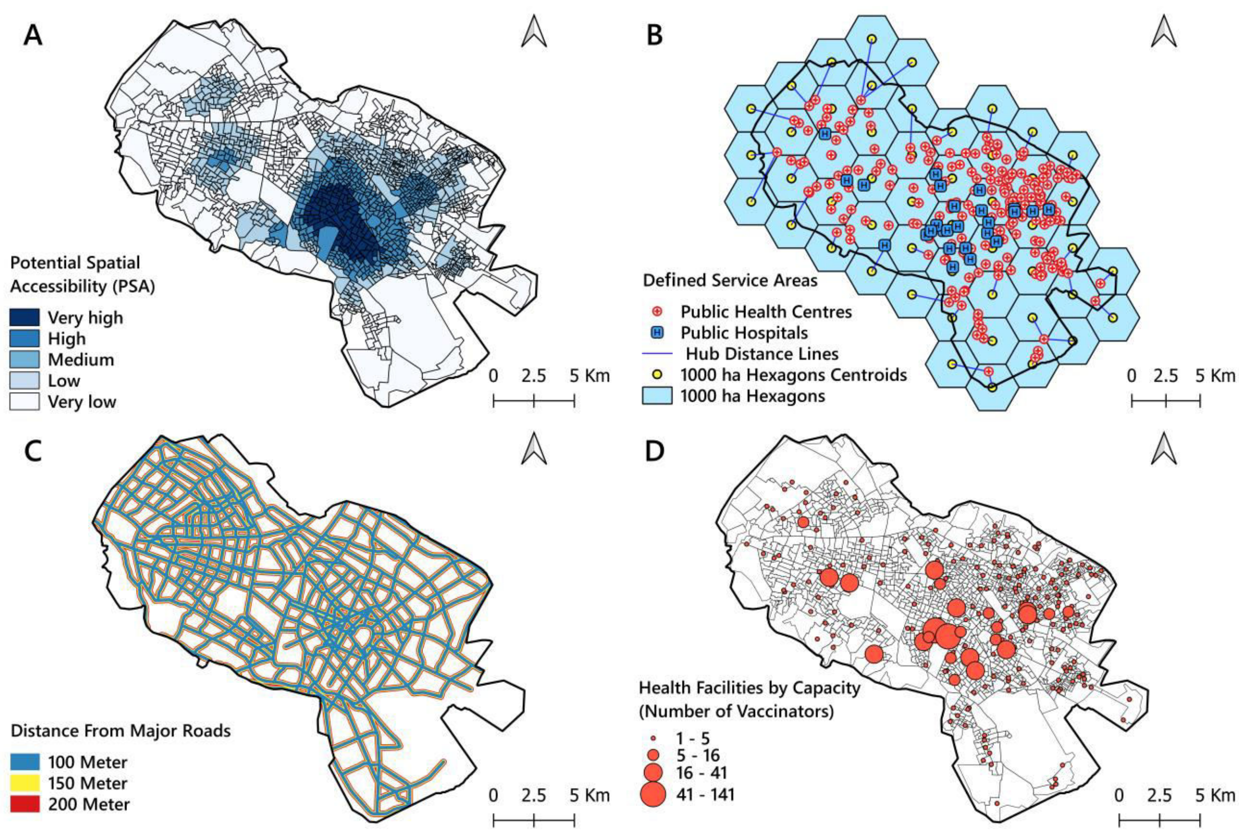

Figure 2. The criteria used to select potential COVID-19 vaccination centres

A: PSA to PHs and PHCs. B: User-defined equal-size hexagons as optimum service areas of potential vaccination centres; C: Distance from major roads; D: Capacity of potential vaccination centres.

2-5-Accessibility to PVCs (reallocated centres)

After selecting the PVCs, the PSAs to these facilities were measured using the E2SFCA methodology as described.

2-6-Evaluation of the model

Global Moran's Index (GMI) was used to measure the spatial autocorrelation of the accessibility index in different scenarios and the proposed model. We assumed that a decrease in spatial autocorrelation of accessibility within CAs indicated improved accessibility. The GMI is defined by Eq. 4 (45):

Eq.4

$$I = \frac{n\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)\right)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)\left(\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right)}$$

where n is the total number of spatial divisions (i.e. the CTs); x_i the value of the PSA in CT i; $\bar{x}$ the arithmetic mean for a given PSA; and w_{ij} the spatial weight matrix based on inverse distance and the Euclidean distance (distance band=2983.7 m and the number of nearest neighbours=4). The value of Moran's I ranges from −1 to +1. The further away it is from zero, the stronger (positive or negative) the autocorrelation (46). To calculate the GMI, the univariate Moran's I analysis in ArcGIS v.10.8, software was used. A p-value <0.01 was considered significant in the test using 99 permutations.

2-7- Visualisation of the selected PVC areas of influence

This was done by Thiessen polygons, generated around a set of points in a given space by assigning all locations in that space to the closest member of the point set, a type of spatial tessellation called Voronoi diagrams (47, 48). Each polygon was created by QGIS and can be seen as an area of influence of a point in the given set (47, 48). The CTs were introduced as the origins and the PVCs as the destinations. In Figure 4, the hub-distance (shown as red lines) indicates the distance (in km) from the centre of each CT (origin) to the nearest PVC (destination). The boundaries (in black) of the Thiessen polygons indicate the coverage of the service area of each PVC (Figure 4-A).

2-8-Software

All analyses were performed using ArcGIS v.10.8 software (ESRI, Redlands, CA, USA) and QGIS v.3.20 open-access software v.3.20 (https://qgis.org/en/site/forusers/download.html). All maps and charts are based on QGIS calculations. Business Performance Management, Singapore (BPMS) free web-based AHP online system (49) was used to calculate the weights of the various criteria.

3-Results

3-1-Access to public hospitals as PVCs

Preliminary results indicated that 864 CTs (66.4%) had low access to PHs (PSA <0.000072) (Fig. 3-A). Also, those CTs with above-average access to PVCs are often located in central parts of the city, where also most of the PHs (60%) are located. Moreover, the PSAs in 157 CTs (12.1%) were zero, mainly in the peripheral parts of the city and far from medical facilities and PHs.

3-2-Access to public health centres

Out of the CTs, 768 (59.0%) had low access to the PHCs (PSA <0.000052), which is illustrated by Fig. 3-B. In only one CT, the PSA value was zero. This suggests that once the COVID-19 vaccine is available for all in all PHCs, most areas of the city would receive equitable vaccination services, even those with low PSA values. In contrast, areas with higher-than-average PSA values were almost always found to be located in the eastern and north-eastern parts of the city. Hence, the spatial distribution of PSA values of the PHCs was not quite similar to the spatial distribution of PSA values of the PHs.

3-3-Access to PHs and PHCs

The average value of PSA in the third scenario was 0.00001. According to Fig. 3-C, 825 CTs (63.4%) had low access to these PVCs (PSA <0.00001). Moreover, in 11 CTs (0.08%), the PSA value was zero. The CTs with higher PSA values were often seen to be located in central parts of the city.

3-4-Access to selected PVCs (the proposed model)

Figure 3-D depicts the results of the E2SFCA method for measuring access to the selected PVCs. Although only 60 centres out of 297 (20%) were included in the model, the average PSAI was 0.000012, which indicates that 794 CTs (61.0%) have low access to PVCs (PSA <0.000012). In 37 CTs (2.8%), the PSA value was zero. Moreover, the spatial distribution of PSA in this model was almost similar to the geographical pattern in the third scenario (i.e. the combination of PHS and PHCs). However, PSA to PVCs was very low in the CTs located in all the suburban areas of the city.

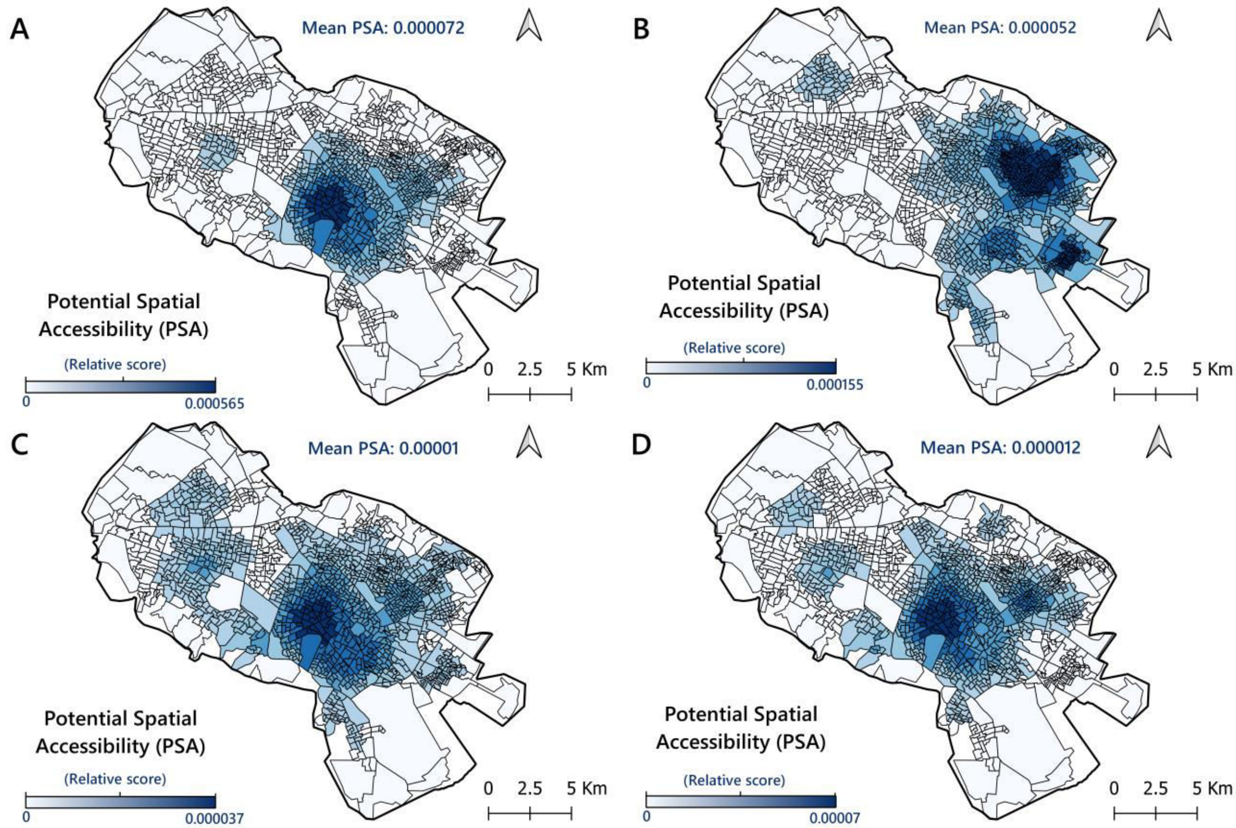

Figure 3 Spatial distribution of PSA to COVID-19 vaccination centres

A: PSA to public hospitals; B: PSA to public health centres; C: PSA to public hospitals and public health centres; D: PSA to the selected centres for performing vaccination.

3-5- Model Evaluation

Table 1 shows the summary statistics for spatial autocorrelation for the three scenarios and the proposed model. Moran's *I* for the first scenario (PSA to PHs) was 0.6 (Z-score=182.52, $p<0.01$) indicating a clustered and unequal distribution of the PSA to hospitals in the city. The value of this index for the PSA for the second scenario (PSA to PHCs) was 0.75 (Z-score=226.40, $p<0.01$). For the third scenario (PSA to PHs and PHCs), this index was 0.57 (Z-score=173.40, $p<0.01$). Moran's *I* and the Z-score values decreased in the third scenario, indicating a more uniform distribution of the PSA index compared to the first two scenarios. Finally, the value of GMI for the proposed model (PSA to selected PVCs) was calculated as 0.53 (Z-score=162.42, $p<0.01$). Both GMI and Z-score values decreased in the proposed model, suggesting an enhancement in PSA to COVID-19 vaccination services.

Table 1. Results of spatial autocorrelation (GMI) of three vaccination scenarios and the proposed model based on PSA

PSA	Global Moran Summary			
	Moran's *I*	Z-score	*P*-value	Distribution pattern
***Scenario 1*: Hospitals**	0.60	182.52	0.00	Clustered
***Scenario 2*: Health Centres**	0.75	226.40	0.00	Clustered
***Scenario 3*: Hospitals & Health Centres**	0.57	173.40	0.00	Clustered
***Proposed Model*: Top 20% PVCs**	0.53	162.42	0.00	Clustered

PSA = potential spatial access; PVC = potential vaccination centre.

3-6-Visualisation of the selected PVCs' areas of influence

Figure 4-A shows the "areas of influence" (i.e. the service areas) of the selected PVCs based on Thiessen polygons. According to this map, each CT is connected to the nearest PVCs for vaccination services (average distance = 0.99 km). The analysis based on area of influence indicates that even though in the central parts of the city the PSA value is still high; all CTs across the city have access to at least one of the PVCs. Figure 4-B depicts an overview (zoomed in) map of the Thiessen polygons in the Central Business District (CBD) of the city. According to Figure 4-C, the CTs located at a range distance of 0 to 5 km from the CBD, had the highest PSA values, while the PSA values were decreased for the CTs far from the CBD.

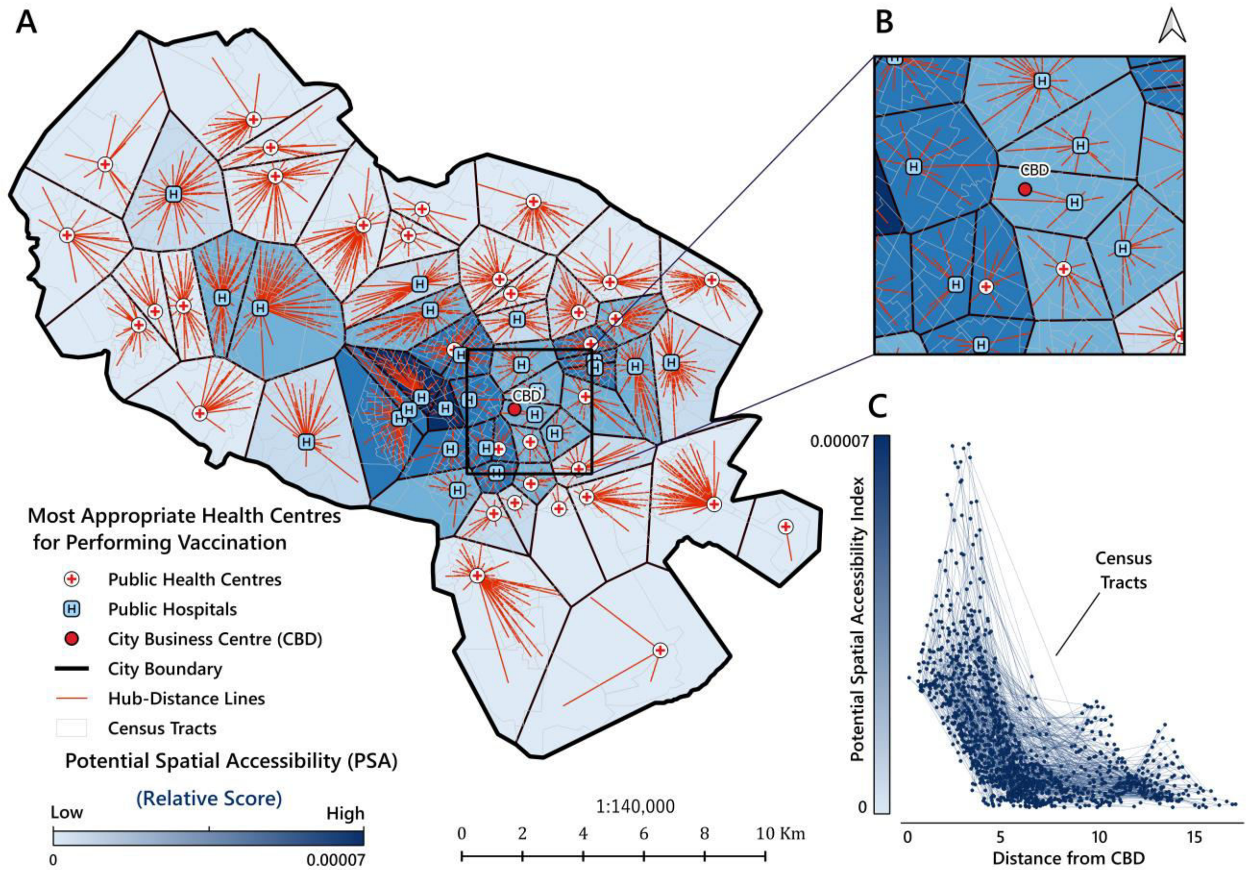

Figure 4. Proposed distribution for allocating potential COVID-19 vaccination centres

A: Areas of influence map of top 20% potential vaccination centres; B: Magnified window of map A focused on CBD area; C: The relationship between PSA and distance from the CBD area. The strength of the blue colour Thiessen polygon ramp indicates the relative score of the PSA.

4- Discussion

We developed an application of the E2SFCA method for identifying the location of vaccinations centres by incorporating the CT population age structure to obtain a more realistic measure of PSA in the metropolitan area. Although the research methodology was developed for a specific place, Mashhad City in Iran, the methodology is replicable and can be applied in any urban area when vaccination supply, urban population, road network and the average driving speed is known. The PSA to PHs (first scenario) measurements showed low values of PSA for a large number of CTs. Additionally, the results of GMI showed a clustered distribution of PSA in this scenario because the hospitals are mainly concentrated in the city centre, with no homogeneous distribution across the study area. This should be considered when planning hospitals and health centres in rapidly growing developing countries, where an unequal distribution of hospitals with a concentration in the central metropolitan areas is not unusually the end result (20). Consistent with the findings of Pereira et al. (26) in Brazil, our study found that there is an intense spatial inequality between downtown areas and marginal poor neighbourhoods with respect to access to PHs and PVCs. Our findings also suggest that a significant number of CTs around the city had virtually no access to COVID-19 vaccinations due to the dearth of hospitals there. However, although hospitals have a greater capacity for vaccination than any other health facilities, this criterion alone is not sufficient to provide equitable access vaccination services in metropolitan areas. To reduce disparities and remedy this situation, public health policymakers should take into account all available vaccination places to defy the uneven coverage.

Findings of PSA measurements in the second scenario showed that the average total accessibility to PHCs was lower than the average PSA to PHs due to a general lower PHC capacity. However, according to this scenario, it is possible to provide services for many CTs since the number of CTs accessing the PVCs was 7% higher than in the first scenario. Moreover, the results of GMI for this scenario showed that the PSA to PHCs had a highly clustered distribution, suggesting that these centres were not uniformly distributed in the city (they were in fact highly concentrated in the north-eastern areas). Therefore, this scenario may not be a realistic choice for providing spatial access to COVID-19 vaccination services. As stated by Jacobson et al. (50), many developing countries often encounter a shortage of vaccines which should be optimally distributed by the providers. Moreover, according to Shadmi et al. (51), despite the availability of vaccines in major cities of developing countries, many barriers can prevent spatial access to the PVCs, such as uneven spatial distribution of health facilities and improper transportation systems.

PSA measurements related to the third scenario indicated that more CTs could receive appropriate vaccination services than in the first scenario. The GMI also showed that the spatial distribution of PSA tended towards a less clustered pattern compared to the first and second scenarios. This means that PVCs can be available to residents in a wider geographic area. The results support the notion that the number of CTs with PSA=0 decreased to 0.84% compared to the first scenario in the third scenario, with the result that the third scenario stands out as providing more equitable spatial access. However, similar to the second scenario, it is impossible for government and local authorities to equip 297 centres. Therefore, this scenario cannot properly provide COVID-19 vaccination for a metropolitan area, especially not in developing countries with limited financial resources.

The PSA results of the proposed model indicates that, despite the selection of only 20% of high-capability centres as COVID-19 vaccination services, more CTs would have access to COVID-19 vaccination centres than in the first and third scenarios. Second, the GMI results show that the spatial distribution of PSA is less focused than the other scenarios, with a decreased strength of PSA clustering. This means a more equitable distribution of PVCs and effective criteria in selecting PVCs by improving the PSA. Despite selecting high-priority centres for vaccination, the PSA rate in the proposed model was still high in some areas, including the centre and the areas surrounding the CBD. In contrast, the rates were close to zero in other areas due to the high concentration of health facilities in metropolitan areas, as seen in too many developing countries (52). Similar to the findings of Zhao et al. (52) in Beijing, China, the public transportation system of our study area is unevenly distributed, with most transportation facilities (e.g., buses and metro stations) concentrated in the city centre. According to Kenyon et al. (53), the obstacles associated with transportation can worsen disparities in access to health facilities such as vaccination centres. As expressed by Tseng et al. (54), supply capacity and the service area of a catchment in the E2SFCA method need to vary based on the type of supply. Therefore, we considered the number of vaccinators in this study as supply capacities to selected PVCs. Thus, to maximize service coverage, the defined service areas were considered for vaccine supply centres. These designated areas allowed us to choose the most accessible centres to provide vaccine services to all city areas. At the same time, the analysis results with reference to the areas of influence showed that despite restrictions to equitable access (<1 km), all CTs had access to at least one available centre for performing COVID-19 vaccination. This 1-km threshold can be suitable for metropolitan areas, especially in developing countries, during a short-time vaccination programme.

There are several limitations in this study that are mainly associated with the data quality. First, the road network dataset did not contain traffic information to apply multi-modal travel-time techniques. Second, the data for estimating the flow of residents during day and night were not available. In spite of the above-mentioned limitations, the results of this study can contribute to pandemic-related policymaking at the local level.

Based on the findings of this study, policymakers should pay attention to a more equitable distribution of primary healthcare facilities in large cities for long-term health planning. As it is difficult to employ all health facilities for administrating COVID-19 vaccination in large cities, particularly in developing countries, quantifying the priority of the existing centres for performing vaccination against COVID-19 is inevitable. Further studies should consider dynamic and multi-modal travel-time methods to measure PSA, for example, using mixed indicators to select COVID-19 vaccination centres. In addition, as the COVID-19 vaccine is free of charge for all people, future research should focus on acceptability and accommodation components by addressing ways to improve vaccine availability for vulnerable populations. It is also suggested that future studies combine spatial and non-spatial indicators in measuring the accessibility of COVID-19 vaccine services.

Research implications:

- When choosing vaccination sites, it is necessary to use community health centres in addition to hospitals to decrease spatial inequality.
- To achieve more efficient COVID-19 vaccination, GIS can be used to quantify the suitability of existing healthcare centres in urban areas.
- Modelling of equitable COVID-19 vaccination services in metropolitan areas not only needs to include healthcare centre capacity, but also transportation networks and spatial access as they jointly influence the availability of vaccination.

5- Conclusion

Our findings have important policy implications. The results show that the periphery and poor areas of the city had the least access to PVCs. Therefore, due to the large size of the study area and as it is common for people with lower socio-economic status to commute using public transportations, it is suggested to provide vaccination services in neighbourhoods with better access to public transportation.

The spatial accessibility models can measure the accessibility to potential vaccination services so that all individuals would have adequate and equitable access to COVID-19 vaccination services. We found that using urban indicators in selecting the most appropriate health facilities can help policymakers improve the accessibility to COVID-19 vaccination services in a cost-effective and timely fashion. In addition, the proposed approach in this study can be easily automated and broadly applied to various urban settings.

List of abbreviations

PSA: Potential Spatial Accessibility
2SFCA: Two-step Floating Catchment Area
E2SFCA: Enhance Two-step Floating Catchment Area
ICU: Intensive Care Unit
CA: Catchment Area
CTs: Census tracts
GIS: Geographical Information Systems
PHs: Public Hospitals
PVC: potential vaccination centre
PHCs: Public Health Centres
AHP: Analytical Hierarchy Process

Declarations:

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and/or analysed during the current study are available in the HARVARD Dataverse repository, [https://doi.org/10.7910/DVN/PNQUKX].

Competing interests

The authors declare that they have no conflict of interest.

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Authors' contributions

Alireza and Behzad analysed the data and drafted the manuscript. Abolfazl and Robert critically revised the manuscript. All authors contributed on study design. All authors approved final version for submission.

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