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Optimizing mobile mammography deployment in Oklahoma 2024: a two-step floating catchment area approach

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Abstract

This study assessed spatial accessibility to fixed mammography centres across Oklahoma State, USA using the Two-Step Floating Catchment Area (2SFCA) and the Enhanced Two-Step Floating Catchment Area (E2SFCA) methods to identify areas with limited or no access. For this analysis, we used data from the mammography facilities database of the US Food and Drug Administration verified by direct contact with the facility and the U.S. Census block group population and demographics for women aged 40 years and older. Analyses were stratified by urban areas; large rural areas; and small rural areas. Accessibility scores were calculated using the 2SFCA method with 30-minute drive times and the E2SFCA method with drive times of 10, 20 and 30 minutes weighted by distance decay. Block groups were categorized into quartiles based on accessibility scores. Among 940,994 eligible women, 10% lived in areas with no access. Small rural regions faced the greatest barriers. Spatial disparities were linked to racial and socioeconomic differences: non-Hispanic American Indian/Alaska Native and non-Hispanic White populations were more likely to reside in no-access zones, while Black and Hispanic populations clustered in high-access urban areas. Spatial analysis reveals significant rural disparities in mammography access. Mobile machines should prioritize underserved rural regions to improve equity.

Key words: health disparities; rural; urban; mammography; screening; USA.

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Introduction

Breast cancer is the leading cause of cancer in the United States (US), with an estimated 313,510 cases in 2024 (Siegel *et al.*, 2024). It is the fourth leading cause of cancer death, with an estimated 42,780 deaths in 2024 (Siegel *et al.*, 2024). Early detection through mammography significantly improves survival rates (Berry *et al.,* 2005; Kaplan *et al.*, 2015; Maiz *et al.*, 2020). Mammography screening, although high, is not universal, with 71.3% of women aged 40 years and older in the US receiving mammography screening in the past two years in 2024 (Centers for Disease Control and Prevention, 2024). Mobile screening vans are crucial in improving access to cancer screening, especially for underserved and rural communities (Fontenoy *et al.*, 2013; Greenwald *et al.*, 2017; Stanley *et al.*, 2017; Vang *et al.*, 2018; McElfish *et al.*, 2019; Spak *et al.*, 2022). They bring life-saving breast cancer screening services directly to areas where healthcare facilities may be scarce or difficult to access, and the mobile vehicle approach helps reduce disparities by reaching populations that face barriers, such as limited transportation, financial challenges, or busy schedules (Maheswaran *et al.*, 2006; Fontenoy *et al.*, 2013; Greenwald *et al.*, 2017; Stanley *et al.,* 2017; Vang *et al.,* 2018; Torrez *et al.,* 2024).

American Cancer Society recommendations currently state that women aged 40-44 years can begin screening yearly, and women aged 45 should get a mammogram every year until age 55, after which the recommendation is to do so every one or two years. The US Preventive Services Task Force recommends that all women get screened for breast cancer every other year, starting at age 40 and continuing through age 74. At this time, it is neither recommended nor not recommended, but shared decision-making is suggested for women of age 75 years and older (Richman *et al.*, 2023). Accessibility of screening reflects both spatial and non-spatial factors. Non-spatial accessibility issues include, for example, acceptability, cost, perceived quality of services, socioeconomic barriers to services and structural racism (Alexandraki & Mooradian, 2010; Stoll *et al.*, 2015; Miller *et al.*, 2019; Aleshire *et al.*, 2021; Henderson *et al.*, 2024; Trentham-Dietz *et al.*, 2024; US Preventive Services Task Force *et al.*, 2024). Spatial accessibility encompasses factors such as distance, congestion, traffic patterns and road construction (Chen *et al.*, 2020). There are several ways to measure spatial accessibility, for example, including the population-to-provider ratio, simple buffers (such as Euclidean and service area or time catchment areas) or floating catchment areas (McGrail & Humphreys, 2009; McGrail, 2012). Population-to-provider ratios are used by the Health Resources and Services Administration of the US Department of Health and Human Services in health professional shortage areas or medically underserved areas. The problem with population-to-provider ratios is that they use administrative areas, which often do not capture the day-to-day movement of people. In the US, movement between counties and states is unrestricted; however, there are still barriers to accessing services across state lines, including state-based insurance and Medicaid program limitations. These ratios are essential when planning services for that administrative district, but other factors are more critical for cross-district planning services. Simple buffers are areas around a point, such as a mammography centre, which can be defined by a Euclidean distance (circulating the point) or a time-based area (such as a 30-minute travel area around a point) are often used. The problem with these buffers is that they assume full accessibility within the buffer, an abrupt fall-off and no access outside the buffer.

Unlike fixed methods, a Floating Catchment Area (FCA) is a spatial analysis method that evaluates accessibility, or the provider-to-population ratio based on a specific radius or boundary across administrative boundaries. Such an area incorporates the idea that population demand or resources are mobile and can "float" between locations. Supply and demand are the economic concepts that describe the relationship between the quantity of a resource (supply) and its availability and the desire of consumers to purchase that resource (demand). It is vital that facilities be in areas of demand or where the population is located. Although this concept is straightforward, implementing a supply-and-demand network can be a complex process.

This study aimed to use Two-Step Floating Catchment (2SFCA) and Enhanced Two-Step Floating Catchment (E2SFCA) using time to determine the spatial accessibility of fixed mammography centers in Oklahoma. These approaches have been used to determine the spatial accessibility of primary care physicians (Luo, 2004; McGrail & Humphreys, 2009; McGrail, 2012; Gao *et al.*, 2016), hospitals (Gao *et al.*, 2021; Kiani *et al.*, 2021; Raeesi *et al.*, 2023), medical clinics (Ngui & Apparicio, 2011; Vadrevu & Kanjilal, 2016), pulmonary rehabilitation facilities (Matthews *et al.*, 2019), pharmacies (Zhou *et al.*, 2021), fire stations (Kiran *et al.*, 2020), urban parks (Hu *et al.*, 2020), residential care facilities (Ni *et al.*, 2015), daycare centres (Fransen *et al.*, 2015), food access (Chen, 2019) and mammography facilities (Maheswaran *et al.*, 2006; Eberth *et al.*, 2014). Our goal was to identify geographic areas with women who lack ready access to fixed mammography facilities. A secondary goal was to compare the results of the two methods. The 2SFCA estimates the number of mammography radiographic imaging machines per 100,000 women, while the E2SFCA provides a more accurate picture because it is used to assess three rings of the service area. However, interpreting E2SFCA is more complex and does not allow the determination of the mammography centre to population ratio.

Materials and Methods

Study area

The study area was the catchment area for the University of Oklahoma's Stephenson Cancer Center, which is the state of Oklahoma. This state encompasses almost 181,038 km^2 near the centre of the 48 contiguous US states. Oklahoma had an estimated population of 4,053,824 in 2024, corresponding to a population density of 22.4 people per km^2, which is reported to be 64.6% White; 7.2% American Indian or Alaska Native (AI/AN); 6.8% Black or African American; 2.3% Asian; 0.2% Native Hawaiian or other Pacific Islander (NH); and 3.8% other races (US Census Bureau, 2024). Additionally, 15% reported being multi-racial and 12.9% reported being Hispanic (US Census Bureau, 2024). When accounting for AI/AN populations as one group or in combination with one or more races, the percentage was 14.3%. Oklahoma is home to 38 tribal nations. A higher proportion of Oklahomans live in poverty compared to the US (15.9% *vs*. 12.5%) and are uninsured (11.4% *vs*. 7.9%) (US Census Bureau, 2024).

Data

For supply and locations of mammography screening locations, we utilized the Mammography Facilities Database of the US Food and Drug Administration (FDA) (2024). Because they are not accessible to all populations, we performed the analysis excluding fixed mammography machines in Indian Health Services facilities (5), tribal health facilities (17), urban Indian clinics (2), including both Veteran's Administration (VA) and Department of Defense (DOD) facilities (2) for a total of 134 mammography facilities in the study area. Our team contacted the facilities to determine the number of mammography machines used for screening. When calls were made, two new facilities were located, while 21 no longer performed mammography and 23 either did not answer or refused. However, they were found through advertisement on the Internet as offering mammography service, so we assumed they had one machine. We identified 115 facilities with one or more mammography machines located in their facility (Figure 1); among those, we identified 80 located within the borders of Oklahoma, with the remaining 35 outside of the state (15 in Texas, 9 in Kansas, 6 in Arkansas, and 5 in Missouri). They ranged from one to six machines in the facility, with most (n=90) having only one machine. For analysis, we included all mammography centres within a 30-minute drive time service area in Oklahoma, including those in surrounding states.

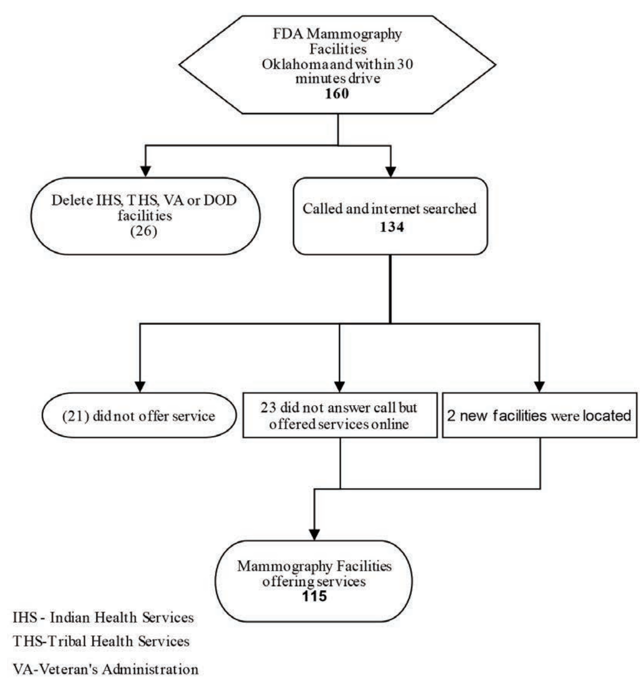

Figure 1. Workflow for Oklahoma mammography screening facility location.

For the demand or population data, we used the 2022 US Census block group geography, the lowest geographic unit that includes population by sex and age. Based on recommended ages for mammography screening (US Preventive Services Task Force, 2024), we obtained the number of women aged 40 years or older from the National Historical Geographic Information System for 2018-2022 (Manson *et al.*, 2024). While we recognized that screening is neither recommended nor discouraged for women aged 75 years and older, we also recognized that many women and their physicians continue screening for various reasons (Schrager *et al.*, 2020; Braithwaite *et al.*, 2023; Lee *et al.*, 2023; Dickson-Swift *et al.*, 2024). For this study, we converted the block group polygons to centroid points to create the demand or population service area. We used the 30-minute driving time to the service area for the 2SFCA and 10, 20, and 30 minutes driving times for the E2SFCA analysis. For analysis purposes, we collapsed those block groups with geographic access to mammography facilities into low, moderate or high access tertiles. We added zero spatial access as a separate group for analysis, which gave four groups: no access, low spatial access (the lowest tertile), moderate spatial access (the middle tertile) and high spatial access (the highest tertile). For demographic data, we examined the entire population of the block group. We included the following variables: general demography (White, Black, AI/AN, Asian, NH and two or more races), ethnicity (Hispanic, non-Hispanic), education (less than high school diploma (GED), equivalent to GED, higher than (GED), civilian unemployment, home tenure (owner vs. renter) and poverty. To measure the degree of rural living (rurality), the United States Department of Agriculture (USDA) Economic Research Service's (ERS) of 2023 and Rural-Urban Continuum Codes (RUCC) were used (Economic Research Service & U.S. Department of Agriculture, 2023). These codes, applied at the county level, refer to the gradual transition and interdependence between rural and urban areas along a spectrum, encompassing various degrees of population density, economic activities and infrastructure development. To analyze different levels of rurality in Oklahoma, large rural counties were included in the RUCC 4-6 group and small rural counties were included in the RUCC 7-9 group. Urban refers to counties in the RUCC 1-3 group. Among the 77 counties in Oklahoma, 18 were urban counties, 28 were large rural counties and 31 were small rural counties.

Analysis

We employed a 2SFCAand a gravity-based E2SFCA analysis to generate accessibility scores for each block group in Oklahoma. The 2SFCA is a spatial accessibility measure that evaluates the availability of services by considering both the supply within a catchment area and the demand, here defined as women aged 40 years and older from surrounding populations. Step 1 calculates the availability of services, or the supply side, at each provider's location, considering the provider's capacity and the population within its 30-minute catchment area. Step 2 identifies all service locations within their catchment area and sums their service-to-demand ratios. For the 2SFCA, we created a 30-minute drive time supply and demand service area. E2SFCA enhances the basic two-step floating catchment method by accounting for variations in service availability and demand. For the E2SFCA, we established drive times of 10, 20 and 30 minutes for supply and demand service areas. E2SFCA typically adjusts for variable travel distances or times, weighting by distance (e.g., closer services are more accessible than those situated further away) using distance weights of 1 for the small 10-minute ring, 0.68 for the second 20-minute ring and 0.22 for the third 30-minute ring (Hashtarkhani *et al.*, 2024). Compared to more straightforward measures, this method provides a more realistic and detailed assessment of spatial access to services. For our analysis, we utilized both the classic and the E2SFCA models developed by Hashtarkhani (2024) and Hashtarkhani et al. (2024), employing the travel time tool in ArcGIS Pro v. 3.4.2, (ESRI, Redlands, CA, USA).

Sensitivity analysis

We performed two sensitivity analyses, excluding 20% and 50% of AI/AN women. These analyses were conducted to account for the exclusion of Indian Health Services, tribal health services and urban (ITU) fixed mammography facilities. Since we excluded the ITU facilities from this analysis, we were able to assess the impact of these exclusions as shown in the supplemental material.

Geocoding and mapping

For the geocoding and service area development of mammography facilities and block group geography, we used the ESRI Street Map for the 3rdquarter of 2024. For visualization purposes, we clipped the features of the final map to represent just Oklahoma. Data were projected to the USA contiguous equidistant conic. All analyses were performed using ArcGIS Pro.

Results

An estimated 940,994 eligible women (aged 40 years and older) residing in Oklahoma from 2018 to 2022 were located in 3,374 block groups (Table 1). The mean population of the block groups was 279 with a standard deviation (SD) of 156.4, ranging from 0 to 1,056.

Two-step floating catchment analysis (2SFCA)

Among eligible women, 95,756 lived in 371 (11%) block groups without access to fixed mammography centres within 30 minutes, and another 279,849 (28%) lived in block groups with low spatial access to fixed mammography locations (Table 1). Among those block groups in areas of high spatial access, 100% were in urban areas, compared to 91% in moderate spatial access areas, 26% in low spatial access areas, and 21% in zero spatial access block groups (Figure 2). Among those block groups in areas without spatial access, 59% were located in small rural counties, compared to 0% in high spatial access areas and 3% and 24%, respectively, in moderate and low spatial access areas. Large geographic parts of Oklahoma lack access to fixed mammography services (Figure 3); in particular, large sections of north-western and south-eastern Oklahoma lack spatial access to these services. Using the 2SFCA method, 51% of Oklahoma's geographic area (expressed in km^2) was found to lack spatial access to fixed mammography services (Table 1).

Enhanced two-step floating catchment analysis (E2SFCA)

Among eligible women, 96,101 (10%) lived in 372 (11%) block groups without spatial access to fixed mammography centres within 30 minutes, and another 280,114 (30%) lived in a block group with low spatial access to fixed mammography facilities (Table 1). Among those block groups in areas of high spatial access, 100% were in urban areas compared to 63% in moderate spatial access areas, 25% in low spatial access areas and only 12% in areas without spatial access to fixed mammography facilities (Figure 2). Again, we saw that large parts of Oklahoma lack access to fixed mammography services (Figure 4), including north-western and south-eastern Oklahoma. Using the E2SFCA method, 90% of Oklahoma's geographic area was found to lack access to fixed mammography services.

E2SFCA compared to 2SFCA

Overall, there are very few differences between the 2SFCA and the E2SFCA. We noted similar patterns regarding no spatial access to fixed-site mammography facilities within 30 minutes in overall or the urban, large rural, and small rural areas, with both methods showing 18%, 21%, and 61%, respectively (Tables 1 and 2). The major difference noted was in the number of block groups that were moderate or low in the large rural area. Using the 2SFCA, only 7% of moderate access block groups were in large rural areas compared to 21% using the E2SFCA area (Table 2). Also, using the 2SFCA method, 50% of low-access block groups were in large rural areas, compared with 31% using the E2SFCA method (Table 2).

Demographic analysis

In evaluating population demographics in relation to spatial access to fixed-site mammography services, we observed a higher proportion of White population in areas with low or no spatial access (both at 71%) within 30 minutes using either 2SFCA or E2SFCA (Table 3). Additionally, Black populations were more

Table 1. Comparison of the two catchment methodologies in relation to levels of access to fixed mammography centres within 30 minutes.

Spatial access	Block groups number (%)		Women ≥40 years old number (%)		Areal size km^2 (%)	
	2SFCA	E2SFCA	2SFCA	E2SFCA	2SFCA	E2SFCA
High	919	1	224,699	247,773	2,1	1,677
	(27.2)	(29.6)	(23.9)	(26.3)	(1.2)	(0.9)
Moderate	1,083	995	340,69	317,006	19,982	16,374
	(32.1)	(29.5)	(36.2)	(33.7)	(11.0)	(9.0)
Low	1,001	1,007	279,849	280,114	65,965	69,763
	(29.7)	(29.8)	(29.7)	(29.8)	(36.4)	(38.5)
Zero	371	372	95,756	96,101	92,991	93,225
	(11.0)	(11.0)	(10.2)	(10.2)	(51.4)	(51.5)
Total	3,374		940,994		181,038	

2SFCA, two-step floating catchment area; E2SFCA, enhanced two-step floating catchment area.

Table 2. Comparison of the two catchment methodologies in estimating spatial access to fixed-site mammography facilities within 30 minutes.

Target	2SFCA				E2SFCA			
	High Number (%)	Moderate	Low	Zero	High	Moderate	Low	Zero
Block group								
Urban	918 (99.9)	973 (89.8)	239 (23.9)	66 (17.8)	1 (100)	880 (88.4)	250 (24.8)	66 (17.7)
Large rural	1 (0.1)	70 (6.5)	503 (50.2)	78 (21.0)	0 (0.0)	78 (21.0)	496 (31.3)	78 (21.0)
Small rural	0 (0.0)	40 (3.7)	259 (25.9)	227 (61.2)	0 (0.0)	37 (3.7)	261 (25.9)	228 (61.3)
Block group population								
Urban	224,235 (99.8)	309,272 (90.8)	71,361 (25.5)	19,311 (20.2)	247,773 (100)	282,642 (89.2)	74,453 (26.6)	19,311 (20.1)
Large rural	464 (0.2)	21,339 (6.3)	143,005 (51.1)	19,065 (19.9)	0 (0.0)	25,17 (7.9)	139,638 (49.9)	19,065 (19.8)
Small rural	0 (0.0)	10,079 (3.0)	65,483 (23.4)	57,38 (59.9)	0 (0.0)	9,194 (2.9)	66,023 (23.6)	57,725 (60.1)
Coverage (km^2)								
Urban	2,077 (98.9)	11,966 (59.9)	15,156 (23.0)	11,055 (11.9)	1,677 (100)	10,342 (63.2)	17,18 (24.6)	11,055 (11.9)
Large rural	24 (1.1)	5,121 (25.6)	20,997 (31.8)	11,626 (12.5)	0 (0.0)	4,315 (26.4)	21,827 (31.3)	11,626 (12.5)
Small rural	0 (0.0)	2,895 (14.5)	29,812 (45.2)	70,31 (75.6)	0 (0.0)	1,717 (10.5)	30,756 (44.1)	70,544 (75.7)

2SFCA, two-step floating catchment area; E2SFCA, enhanced two-step floating catchment area.

likely to be in block groups with high geographic accessibility (12%) in the 2SFCA and a slightly higher percentage (13%) using the E2SFCA method. We also observed a higher percentage of those populations reporting Hispanic ethnicity in block groups with high geographic access to fixed mammography services where the E2SFCA method showed slightly higher (17% *vs* 19%) percentages. Finally, areas with the highest percentage of AI/AN women were found to be associated with areas with lacking or limited geographic accessibility to non-tribal, non-VA or non-DOD fixed mammography facilities. The proportion of women residing in areas with zero geographic access to fixed mammography centres within 30 minutes and having lower educational attainment (14%), was higher than in areas with better access to fixed mammography centres (12% for high and 9% for moderate) (Table 3). We also observed that the lowest percentage of women living below the poverty line was found among those living in areas with moderate access to fixed mammography service (13% for 2SFCA and 12% for E2SFCA). The block groups with zero spatial access had the highest percentage with no insurance coverage (11% for both). Areas with zero or low spatial access to fixed mammography facilities had the highest homeownership rates (77% for both).

Sensitivity analysis

The sensitivity analysis using the 20% and 50% cut-off points for the proportion of AI/AN population within the study area revealed no significant differences from the primary analysis.

Discussion

This study employed a descriptive approach based on 2SFCA and E2SFCA to identify target areas with limited geographic access to fixed mammography facilities in Oklahoma, with the aim of contribute to planning optimal deployment locations for mobile mammography services. We identified large geographic regions in Oklahoma with limited or no spatial access to fixed mammography services throughout the state, with a concentration in thesouth-east and north-west. The lack lack of access was found to be particularly pronounced small rural areas.

Given that the E2SFCA uses gravity weighting of the 10, 20, and 30-minute rings, we would expect more areas to have low spatial access to fixed mammography facilities. The greater refinement and nuance of the E2SFCA approach compared to the 2SFCA one was noted, particularly in urban areas with high spatial accessibility. In contrast, the 2SFCA exhibited better results in areas characterized by more moderate spatial accessibility, particularly in the Oklahoma City and Tulsa areas

Eberth *et al.* (2014) used the 2SFCA to determine the accessibility of mammography services from 2002 to 2008. The analysis showed a declining availability of mammography services over time, with significant variation in the extent of over- or under-supply across the southern US, including Oklahoma. This study also found that capacity reductions were concentrated in areas with an oversupply of machines, leading to a 68% decrease in the proportion of women residing in areas with excess capacity between 2002 and 2008, possibly due to the fact that many facilities were closed even though they remain on the FDA's list. Conversely, the proportion of women living in areas with poor capacity increased by 10% during the same period and the study by Eberth *et al.* (2014) highlighted a decrease in mammography availability and capacity over time, accompanied by notable differences across states. While our study did not examine the per capita changes in the availability of mammography over time, our survey of mammography facilities found that 16% of facilities listed in the FDA registry no longer provide this service. Not surprisingly, Black and Hispanic populations were more likely to live in areas of high spatial access. In Oklahoma, these different groups are concentrated in urban areas. White and AI/AN populations have a higher proportion in the zero-access area as compared to other racial or ethnic groups as these populations are the highest racial/ethnic groups residing in rural areas. For comparison, in the 2024 Behavioral Risk Factor Surveillance Survey (BRFSS) for Oklahoma among women age 40 and older, 73.2% of NH White populations; 74.2% of NH Black populations; 64.2% of NH American Indian or Alaska Native populations; 73.5% of NH Multiracial populations; and 59.7% of the Hispanic population had had a mammogram in the last two years (Centers for Disease Control and Prevention, 2024). Among block groups with high or moderate spatial access, a higher proportion of estimated individuals reported being Black and Hispanic. The latter low reported rate may be due to non-spatial access issues such as acceptability; cost; perceived quality of services; socio-economic barriers to services; language issues; lack of knowledge about screening; and structural racism (Alexandraki & Mooradian, 2010; Stoll *et al.*, 2015; Miller *et al.*, 2019; Aleshire *et al.*, 2021; Henderson *et al.*, 2024; Trentham-Dietz *et al.*, 2024; US Preventive Services Task Force, 2024).These are key reasons to utilize a mobile mammography van in high-need areas, including both rural and urban settings. However, this paper aimed to examine areas with limited or no access to fixed mammography facilities, and it was found that small rural areas had the most limited or zero spatial access, with a large geographic area of the state having low or no spatial access.

The use of mammography facilities by AI/AN women is difficult to disentangle in Oklahoma. As mentioned previously, AI/AN populations (alone or in combination with at least one other ethnic population) comprise 14.3% of those who live in Oklahoma. For this study, we removed mammogram facilities that were ITUs, as well as VA and DOD facilities that only AI/AN women, veterans, or those in the military can access. It is essential to note that AIAN women may use ITU facilities but are not restricted to them; thus, they were included in this study. Further evaluation of this issue is a project for future analysis. We used two methods to account not using data from ITU facility location AI/AN women in our study, one representing the deletion of 20% of the AI/AN eligible women and another representing the deletion of 50% of AI/AN eligible women. These cut-off points represented low and high boundaries

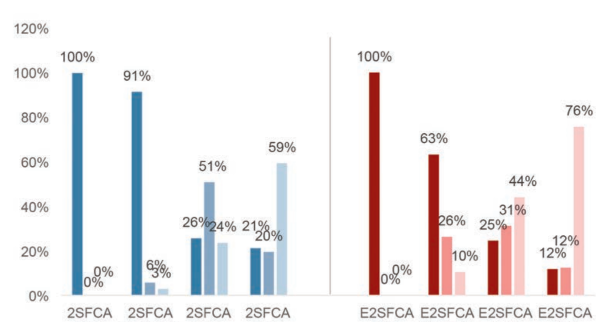

Figure 2. A two-step floating catchment analysis (2SFCA) and enhanced two-step floating catchment analysis (E2SFCA) output block groups by high, moderate, low, and zero spatial access by block group, Oklahoma 2024.

for the estimated number of women being seen in ITU facilities. However, these findings were not substantially different from others described in this study.

Those in moderate spatial access areas had a lower proportion of the proportion of women living in poverty living in poverty in the 2SFCA (13%) and E2SFCA (12%), suggesting that areas with moderate access areas have some of the highest incomes or fewer pockets of poverty. It can be seen that suburban and large rural areas often have moderate areas of spatial access. Additionally, unexpected results showed that the block groups with the highest home ownership (often a proxy for wealth) were situated in areas with no spatial access. This is not surprising given the high homeownership rates in suburban, large, and small rural areas, as well as a higher percentage of rental properties in urban areas (Sani *et al.*, 2023).

The E2SFCA found more high spatial access areas in urban areas than did the 2SFCA. We observed more nuanced results in high and moderate access areas, as well as an increase in low spatial access. This is not surprising given that the third ring (the 20-30 minutes service area) is weighted at just 22%. However, this may reflect reality better as it accounts for the decreased likelihood of women using the fixed mammography centre further out in the 30-minute service area where they reside. When using E2SFCA, we noted that block groups with high access also had higher rates of poverty, higher rates of being uninsured, and slightly higher rates of civilian unemployment. It implies that uninsured women with relatively high rates of poverty live in high-access areas. In these areas, efforts to help women access fixed facilities, such as subsidizing screening costs through funds for breast and cervical

Table 3. Comparison of the two catchment methodologies in relation to the set of variables investigated.

Variable	2SFCA				E2SFCA			
	High % (95% CI)	Moderate % (95% CI)	Low % (95% CI)	Zero % (95% CI)	High % (95% CI)	Moderate % (95% CI)	Low % (95% CI)	Zero % (95% CI)
Demography								
White	64.9 (64.8-65.0)	68.4 (68.4-68.5)	70.5 (70.4-70.6)	71.3 (71.1-71.4)	62.1 (62.0-62.2)	70.9 (70.8-70.9)	70.6 (70.6-70.7)	71.3 (71.2-71.5)
Black	11.8 (11.7-11.8)	8.2 (8.1-8.2)	3.4 (3.4-3.4)	2.7 (2.6-2.7)	13.0 (13.0-13.1)	6.9 (6.9-7.0)	3.4 (3.3-3.4)	2.7 (2.6-2.7)
AI/AN	3.7 (3.7-3.8)	5.9 (5.9-6.0)	11.5 (11.5-11.6)	11.3 (11.2-11.4)	4.2 (4.0-4.2)	5.8 (5.8-5.9)	11.5 (11.4-1.5)	11.3 (11.2-11.5)
Asian	3.4 (3.4-3.5)	3.0 (3.0-3.0)	1.1 (1.0-1.1)	0.5 (0.5-0.6)	3.3 (3.3-3.3)	3.1 (3.1-3.1)	1.1 (1.0-1.1)	0.5 (0.5-0.6)
NH	0.1 (0.1-0.1)	0.1 (0.1-0.1)	0.3 (0.3-0.4)	0.1 (0.1-0.1)	0.2 (0.1-0.2)	0.1 (0.1-0.1))	0.3 (0.3-0.4)	0.1 (0.1-0.1)
Other	4.5 (4.4-4.5)	2.8 (2.7-2.8)	2.5 (2.5-2.5)	3.0 (2.9-3.0)	5.0 (5.0-5.1)	2.2 (2.1-2.2)	2.5 (2.5-2.5)	3.0 (2.9-3.0)
Two or more	11.6 (11.5-11.7)	11.5 (11.5-11.6)	10.7 (10.6-10.7)	11.2 (11.1-11.3)	12.3 (12.2-12.3)	11.0 (11.0-11.1)	10.6 (10.6-10.7)	11.1 (11.0-11.2)
Ethnicity								
Hispanic	17.2 (17.1-17.3)	10.6 (10.6-10.7)	8.6 (8.6-8.7)	9.3 (9.2-9.3)	19.0 (19.0-19.1)	8.6 (8.6-8.7)	8.6 (8.6-8.7)	9.2 (9.2-9.3)
Education								
Less than GED	11.2 (11.1-11.3))	9.2 (9.2-9.3)	12.2 (12.1-12.3)	14.1 (13.914.2)	12.3 (12.2-12.4)	8.3 (8.2-8.3)	12.1 (12.0-12.1)	14.1 (14.0-14.2)
GED level	25.7 (25.6-25.8)	27.7 (27.6-27.8)	36.0 (35.8-36.1)	39.7 (39.5-39.9)	25.7 (25.6-25.8)	27.8 (27.7-27.9)	36.0 (35.9-36.1)	39.7 (39.5-39.9)
Higher than GED	63.1 (63.0-63.2)	63.1 (63.0-63.2)	51.9 (51.8-52.0)	46.2 (46.0-46.4)	62.0 (61.9-62.1)	63.9 (63.8-64.0)	52.0 (51.9-52.1)	46.2 (46.0-46.4)
Below Poverty								
	15.0 (14.9-15.1)	13.4 (13.3-13.4)	17.3 (17.2-17.4)	16.8 (16.6-16.9)	17.1 (17.0-17.2)	11.6 (11.6-11.7)	17.1 (17.1-17.2)	16.8 (16.6-16.9)
Uninsured								
	8.0 (7.9-8.1)	7.8 (7.8-7.9)	9.4 (9.3-9.4)	11.1 (11.0-11.2)	9.2 (9.2-9.3)	6.9 (6.8-6.9)	9.3 (9.3-9.4)	11.1 (11.0-11.2)
Unemployed								
	4.9 (4.9-5.0)	5.1 (5.1-5.2)	5.3 (5.3-5.4)	2.0 (2.0-2.1)	5.1 (5.1-5.2)	4.6 (4.5-4.6)	5.0 (4.9-5.1)	4.8 (4.7-4.9)
Own home								
	59.6 (59.4-59.7)	66.1 (66.0-66.2)	68.1 (68.0-68.2)	76.8 (76.5-77.0)	55.7 (55.6-55.8)	69.9 (69.8-70.1)	68.4 (68.2-68.5)	76.8 (76.5-77.0)

AI/AN, American Indian or Alaska Native; NH, Native Hawaiian and other Pacific Islander; GED, high school diploma; 2SFCA, two-step floating catchment area; E2SFCA, the enhanced two-step floating catchment area.

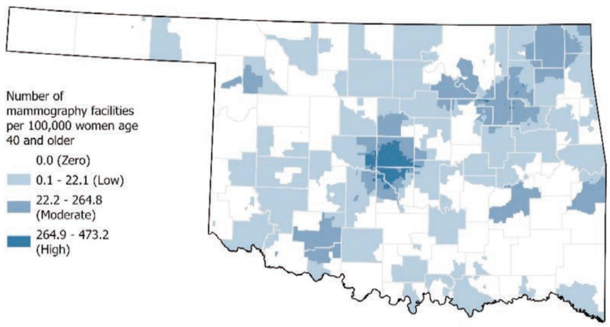

Figure 3. A two-step floating catchment analysis (2SFCA) output block groups by high, moderate, low and zero spatial access by block group.

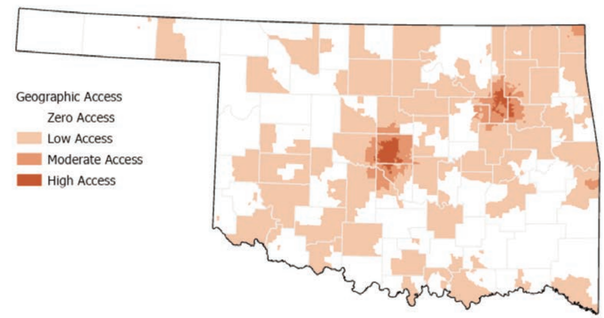

Figure 4. An enhanced two-step floating catchment analysis (E2SFCA) output block groups by high, moderate, low, and zero quartiles by block group.

cancer early detection may make more sense than deploying a vehicle. This study examines only geographic access to fixed facilities. It is essential to note that even people with high geographic access do not necessarily access the service because of health insurance coverage or financial barriers to mammography.

Strengths and limitations

Our study has several strengths, including investigating the small geographic units of the block group. Additionally, we accounted for mammography access for Oklahomans in out-of-state facilities, thus reducing or eliminating the edge effects for the state. The limitations has to do with the out-of-state facilities; we may have overestimated access to fixed facilities along the edges of Oklahoma because of lack of insurance or free and reduced program acceptance. Additionally, traffic congestion, road construction and public transportation lead to uncertainty about travel time as noted elsewhere by Chen *et al*. (2020). For this study, we did not consider travel time uncertainty. While it is an essential factor, it tends to be more critical in urban areas where there is more opportunity for traffic congestion and thus more opportunities to delay travel time. We plan to consider this factor for future work in urban areas that may benefit from mobile mammography. Another difficulty is with the interpretation of the E2SFCA. Because of weighting, we could not estimate the number of women per 100,000 in a geographic area. Another limitation was the difficulty in accessing detailed mammography data; only 83% of calls to mammography facilities were answered when we surveyed them. Some payment sources (such as the Breast and Cervical Cancer Early Detection Program) require the contractor or facility to be in Oklahoma, but this is a limited number of women with 2,378 women being screened by the three program (Oklahoma State Department of Health, Cherokee Nation, and Kaw Nation) in 2021 – the last year for which all three programs data were available (Oklahoma State Department of Health, 2021) we were unable to infer results from individual women. In addition, our study is susceptible to the Modifiable Area Unit Problem (MAUP) because of the block group used, and our results may vary depending on the administrative unit chosen for analysis. We chose the block group for this study because it was the smallest geographic area that provided the age of women in a manner that allowed us to estimate the total population requiring mammography services. However, we recognize that we might come to different conclusions if we had used, for example, census tracts.

Conclusions

Spatial accessibility analyses, including 2SFCA and E2SFCA, revealed that large portions of Oklahoma, especially small rural areas, lack adequate geographic access to fixed mammography centres. Findings emphasize the need for the targeted deployment of mobile mammography machines to address geographic and demographic disparities, thereby ensuring equitable access to breast cancer screening.

References

Aleshire ME, Adegboyega A, Escontrias OA, Edward J, Hatcher J, 2021. Access to Care as a Barrier to Mammography for Black Women. Policy Polit Nurs Pract 22:28-40.

Alexandraki I, Mooradian AD. 2010. Barriers related to mammography use for breast cancer screening among minority women. J National Med Assoc 102:206-18.

Berry DA, Cronin KA, Plevritis SK, Fryback DG, Clarke L, Zelen M, Mandelblatt JS, Yakovlev AY, Habbema JD, Feuer EJ; Cancer Intervention and Surveillance Modeling Network (CISNET) Collaborators. Effect of screening and adjuvant therapy on mortality from breast cancer. N Engl J Med 353:1784-92.

Braithwaite D, Chicaiza A, Lopez K, Lin KW, Mishori R, Karanth SD, Anton S, Miller K, Schonberg MA, Schoenborn NL, O'Neill SC. 2023. Clinician and patient perspectives on screening mammography among women age 75 and older: A pilot study of a novel decision aid. PEC Innov 2:100132.

Centers for Disease Control and Prevention. 2024. Behavioral Risk Factor Surveillance System Survey Data (U.S. Department of Health and Human Services). Available from: https://www.cdc.gov/brfss/annual_data/annual_2024.html

Chen BY, Cheng XP, Kwan MP, Schwanen T. 2020. Evaluating spatial accessibility to healthcare services under travel time uncertainty: A reliability-based floating catchment area approach. J Transport Geogr 87-102794.

Chen, X. 2019. Enhancing the two-step floating catchment area model for community food access mapping: case of the supplemental nutrition assistance program. Professional Geograph 71:668-80.

Dickson-Swift V, Adams J, Spelten E, Blackberry I, Wilson C, Yuen E. 2024. Breast cancer screening motivation and behaviours of women aged over 75 years. Psycho‐Oncology 33:e6268.

Eberth JM, Eschbach K, Morris JS, Nguyen HT, Hossain MM, Elting LS. 2014. Geographic disparities in mammography capacity in the South: a longitudinal assessment of supply and demand. Health Serv Res 49:171-85.

Economic Research Service, & U.S. Department of Agriculture. 202). Rural-Urban Continuum Codes. Retrieved 04/05 from https://www.ers.usda.gov/data-products/rural-urban-continuum-codes

Fontenoy AM, Langlois A, Chang SL, Daigle JM, Pelletier É, Guertin MH, Théberge I, Brisson J. 2013. Contribution and performance of mobile units in an organized mammography screening program. Can J Public Health 104:e193-99.

Fransen K, Neutens T, De Maeyer P, Deruyter G. 2015. A commuter-based two-step floating catchment area method for measuring spatial accessibility of daycare centers. Health Place 32:65-73.

Gao F, Jaffrelot M, Deguen S. 2021. Measuring hospital spatial accessibility using the enhanced two-step floating catchment area method to assess the impact of spatial accessibility to hospital and non-hospital care on the length of hospital stay. BMC Health Serv Res 21:1078.

Gao F, Kihal W, Le Meur N, Souris M, Deguen S. 2016. Assessment of the spatial accessibility to health professionals at French census block level. Int J Equity Health 15:125.

Greenwald ZR, El-Zein M, Bouten S, Ensha H, Vazquez FL, Franco EL. 2017. Mobile screening units for the early detection of cancer: a systematic review. Cancer Epidemiol Biomarkers Prev 26:1679-94.

Hashtarkhani S, Schwartz DL, Shaban-Nejad A. 2024. Enhancing health care accessibility and equity through a geoprocessing toolbox for spatial accessibility analysis: development and case study. JMIR Form Res 8:e51727.

Henderson JT, Webber EM, Weyrich MS, Miller M, Melnikow J. 2024. Screening for breast cancer: evidence report and systematic review for the US preventive services task force. JAMA 331:1931-46.

Hu SJ, Song W, Li CG, Lu J. 2020. A multi-mode Gaussian-based two-step floating catchment area method for measuring accessibility of urban parks. Cities 105:102815.

Kaplan HG, Malmgren JA, Atwood MK, Calip GS. 2015. Effect of treatment and mammography detection on breast cancer survival over time: 1990-2007. Cancer, 121:2553-61.

Kiani B, Mohammadi A, Bergquist R, Bagheri N. 2021. Different configurations of the two-step floating catchment area method for measuring the spatial accessibility to hospitals for people living with disability: a cross-sectional study. Arch Public Health 79:85.

Kiran KC, Corcoran J, Chhetri P. 2020. Measuring the spatial accessibility to fire stations using enhanced floating catchment method. Socio-Econ Planning Sc 69:100673.

Lee CS, Lewin A, Reig B, Heacock L, Gao Y, Heller S, Moy L. 2023. Women 75 Years Old or Older: To Screen or Not to Screen? RadioGraphics 43:e220166.

Luo W. 2004. Using a GIS-based floating catchment method to assess areas with shortage of physicians. Health Place 10:1-11.

Maheswaran R, Pearson T, Jordan H, Black D. 2006. Socioeconomic deprivation, travel distance, location of service, and uptake of breast cancer screening in North Derbyshire, UK. J Epidemiol Community Health 60:208-12.

Maiz C, Silva F, Domínguez F, Galindo H, Camus M, León A, Oddó D, Villarroel A, Razmilic D, Navarro ME, Medina L, Merino T, Vines E, Peña J, Maldonado D, Pinto MP, Acevedo F, Sánchez C. 2020. Mammography correlates to better survival rates in breast cancer patients: a 20-year experience in a University health institution. Ecancermedicalscience 14:1005.

Manson S, Schroeder J, David VR, Katherine K, Tracy K, Finn R, Ruggles S. 2024. IPUMS National Historical Geographic Information System: Version 19.0 [dataset] https://doi.org/http://doi.org/10.18128/D050.V19.0

Matthews KA, Gaglioti AH, Holt JB, Wheaton AG, Croft B. 2019. Using spatially adaptive floating catchments to measure the geographic availability of a health care service: Pulmonary rehabilitation in the southeastern United States. Health Place 56:165-73.

McElfish PA, Su LJ, Lee JY, Runnells G, Henry-Tillman R, Kadlubar SA. 2019. Mobile Mammography Screening as an Opportunity to Increase Access of Rural Women to Breast Cancer Research Studies. Breast Cancer (Auckl) 13:1178223419876296.

McGrail MR. 2012. Spatial accessibility of primary health care utilising the two step floating catchment area method: an assessment of recent improvements. Int J Health Geogr 11:50.

McGrail MR, Humphreys JS. 2009. Measuring spatial accessibility to primary care in rural areas: Improving the effectiveness of the two-step floating catchment area method. Appl Geogr 29:533-41.

Miller BC, Bowers JM, Payne JB, Moyer A. 2019. Barriers to mammography screening among racial and ethnic minority women. Soc Sci Med 239:112494.

Ngui AN, Apparicio P. 2011. Optimizing the two-step floating catchment area method for measuring spatial accessibility to medical clinics in Montreal. BMC Health Serv Res 11:166.

Ni J, Wang J, Rui Y, Qian T, Wang J. 2015. An enhanced variable two-step floating catchment area method for measuring spatial accessibility to residential care facilities in Nanjing. Int J Environ Res Public Health 12:14490-504.

Oklahoma State Department of Health. (2021). Oklahoma Breast and Cervical Cancer Annual Report State Fiscan Year 2021. Available from: https://oklahoma.gov/content/dam/ok/en/health/health2/aem-documents/health-promotion/take-charge/Oklahoma%20Breast%20and%20Cervical%20Cancer%20Annual%20Report%20SFY%202021.pdf

Raeesi A, Tara M, Kiani B. 2023. Spatial accessibility to hospitals in Southeast Iran: an enhanced two-step floating catchment area method. Geojournal 88:5427-43.

Richman IB, Long JB, Soulos PR, Wang SY, Gross CP. 2023. Estimating Breast Cancer Overdiagnosis After Screening Mammography Among Older Women in the United States. Ann Intern Med 176:1172-80.

Sani A, Mohammed MI, Usman H. 2023. Locational, neighbourhood and physical characteristics of residential rental properties: A review. J Commerce Manag Tourism Studies 2:143-54.

Schrager S, Ovsepyan V, Burnside E. 2020. Breast cancer screening in older women: the importance of shared decision making. J Am Board Fam Med 33:473-80.

Siegel RL, Giaquinto AN, Jemal A. 2024. Cancer statistics, 2024. CA: Cancer J Clinicians 74:12-49.

Spak DA, Foxhall L, Rieber A, Hess K, Helvie M, Whitman GJ. 2022. Retrospective Review of a Mobile Mammography Screening Program in an Underserved Population within a Large Metropolitan Area. Acad Radiol 29:S173-79.

Stanley E, Lewis MC, Irshad A, Ackerman S, Collins H, Pavic D, Leddy RJ. 2017. Effectiveness of a Mobile Mammography Program. AJR Am J Roentgenol 209:1426-9.

Stoll CR, Roberts S, Cheng MR, Crayton EV, Jackson S, Politi MC. 2015. Barriers to mammography among inadequately screened women. Health Educ Behav 42:8-15.

Torrez CRZ, Gasior JA, Ginzberg SP, Nunes LW, Fayanju OM, Englander BS, Elmore LC, Edmonds CE. 2024. Identifying and Addressing Barriers to Screening Mammography in a Medically Underserved Community. Academic Radiol 31:2643-50.

Trentham-Dietz A, Chapman CH, Jayasekera J, Lowry KP, Heckman-Stoddard BM, Hampton JM, Caswell-Jin JL, Gangnon RE, Lu Y, Huang H, Stein S, Sun L, Gil Quessep EJ, Yang Y, Lu Y, Song J, Muñoz DF, Li Y, Kurian AW, Kerlikowske K, O'Meara ES, Sprague BL, Tosteson ANA, Feuer EJ, Berry D, Plevritis SK, Huang X, de Koning HJ, van Ravesteyn NT, Lee SJ, Alagoz O, Schechter CB, Stout NK, Miglioretti DL, Mandelblatt JS. 2024. Collaborative modeling to compare different breast cancer screening strategies: a decision analysis for the US preventive services task force. JAMA, 331(22), 1947-1960.

US Census Bureau. 2024. Explore Census Data. Available from: https://data.census.gov/

US Food and Drug Administration. 2024. Mammography Facilities Mammography Facilities. Available from: https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfmqsa/mqsa.cfm

US Preventive Services Task Force, 2024. Screening for Breast Cancer: US Preventive Services Task Force Recommendation Statement. JAMA 331:1918-30.

Vadrevu L, Kanjilal B. 2016. Measuring spatial equity and access to maternal health services using enhanced two step floating catchment area method (E2SFCA) - a case study of the Indian Sundarbans. Int J Equity Health 15:87.

Vang S, Margolies LR, Jandorf L. 2018. Peer reviewed: mobile mammography participation among medically underserved women: a systematic review. Prev Chronic Dis 15:E140.

Zhou Y, Beyer KMM, Laud PW, Winn AN, Pezzin LE, Nattinger AB, Neuner J. 2021. An adapted two-step floating catchment area method accounting for urban-rural differences in spatial access to pharmacies. J Pharm Health Serv Res 12:69-77.

Online supplementary materials
Table S1. Access levels to mammography calculated by E2SFCA excluding 50% of eligible American Indian or Alaska Native women: Oklahoma 2024.
Figure S1. An enhanced two-step floating catchment analysis (E2SFCA) output block groups by high, moderate, low, and zero quartiles by block group recommended women aged 40 and older excluding 50% of eligible American Indian or Alaska Natives women Oklahoma 2024.
Figure S2. An enhanced two-step floating catchment analysis (E2SFCA) output block groups by high, moderate, low, and zero quartiles by block group recommended women aged 40 or more removing 20% American Indian or Alaska Native women: Oklahoma 2024.
Table S2. Access levels to mammography by areal residency for women calculated by E2SFCA excluding 50% of eligible American Indian or Alaska Native women: Oklahoma 2024.
Table S3. Access levels to mammography calculated by E2SFCA excluding 20% of eligible American Indian or Alaska Native women: Oklahoma 2024.
Table S4. Access levels to mammography by areal residency for women calculated by E2SFCA excluding 20% of eligible American Indian or Alaska Native women: Oklahoma 2024

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Conflict of interest: the authors declare no conflict of interest.

Ethical considerations: this study utilized publicly available data, and the University of Oklahoma Health Sciences (IRB) determined that it did not constitute human subjects' research.

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