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Article

Association between a network-based physician linchpin score and cancer patient mortality: a SEER-Medicare analysis

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Abstract

Background: Patients with cancer frequently require multidisciplinary teams for optimal cancer outcomes. Network analysis can capture relationships among cancer specialists, and we developed a novel physician linchpin score to characterize "linchpin" physicians whose peers have fewer ties to other physicians of the same oncologic specialty. Our study examined whether being treated by a linchpin physician was associated with worse survival.

Methods: In this cross-sectional study, we analyzed Surveillance, Epidemiology, and End Results–Medicare data for patients diagnosed with stage I to III non-small cell lung cancer or colorectal cancer (CRC) in 2016-2017. We assembled patient-sharing networks and calculated linchpin scores for medical oncologists, radiation oncologists, and surgeons. Physicians were considered linchpins if their linchpin score was within the top 15% for their specialty. We used Cox proportional hazards models to examine associations between being treated by a linchpin physician and survival, with a 2-year follow-up period.

Results: The study cohort included 10 081 patients with non-small cell lung cancer and 9036 patients with CRC. Patients with lung cancer treated by a linchpin radiation oncologist had a 17% (95% confidence interval = 1.04 to 1.32) greater hazard of mortality, and similar trends were observed for linchpin medical oncologists. Patients with CRC treated by a linchpin surgeon had a 22% (95% confidence interval = 1.03 to 1.43) greater hazard of mortality.

Conclusions: In an analysis of Medicare beneficiaries with nonmetastatic lung cancer or CRC, those treated by linchpin physicians often experienced worse survival. Efforts to improve outcomes can use network analysis to identify areas with reduced access to multidisciplinary specialists.

Improving access to health care is considered paramount to improving patient outcomes and achieving health equity (1-4). Assessing the spatial distribution of health-care professionals is a well-established method for determining access to primary and specialty health-care services (5,6). Workforce reports on the spatial distribution of oncologists from the American Society of Clinical Oncology have shown striking geographic disparities in oncologist density across the United States, with rural areas particularly at risk of oncology workforce shortages (7). Prior research has found elevated cancer mortality rates in regions characterized by low oncologist density and greater travel burden to specialty care (8,9). Because medical, surgical, and radiation oncologists practice within complex systems to coordinate the delivery of multidisciplinary treatment plans, however, measuring access to the physician oncology workforce presents unique challenges (10). Care coordination measures for multidisciplinary cancer care are absent or limited, challenging our ability to assess ways in which the oncology workforce functions across health-care professionals to serve patients with cancer (11).

We hypothesized that integrating characteristics of physician patient-sharing networks into measurement of the oncology physician workforce would better capture the structure of the multidisciplinary relationships linking physicians and patient outcomes. Relationships among physicians represent an aspect of health-care access that could affect both potential and realized access to care as well as outcomes—that is, a cancer physician's patient outcomes may be intertwined with that physician's multidisciplinary patient-sharing network and experience coordinating care with peers. We have developed a network measure that identifies physicians who are vital for bringing their specialty's expertise to the region—in other words, a "linchpin" (12). For example, a medical oncologist's linchpin score assesses the extent to which their peers (physicians from

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other specialties with whom they share patients) are connected to other medical oncologists. Being a linchpin oncologist could be reflective of a health-care delivery system that has reduced specialist access, fewer resources, lower competition among specialists, and geographic or other barriers to establishing interdisciplinary relationships between clinicians.

In our prior work examining linchpin oncologists in a cancer patient-sharing network assembled from nationwide Medicare claims, we found that linchpin oncologists were more likely to practice in nonmetropolitan areas than oncologists who were not characterized as linchpins (13). We also found that hospital referral regions with a higher-than-expected proportion of linchpin oncologists tracked with indicators of socioeconomic disadvantage and lower rates of radiation therapy receipt. A better understanding of how physician relationships are associated with overall survival is critical to guide efforts aimed at reducing the disparities in cancer mortality that have been observed across race, rurality, and socioeconomic status (3,14-17).

The objective of this study was to assess the extent to which being treated by linchpin medical, surgical, or radiation oncologists (herein referred to as *oncologists*) is associated with survival in patients with cancer. In this study, we focused on outcomes for patients with nonmetastatic non-small cell lung cancer (NSCLC) or colorectal cancer (CRC) because these diseases often require multidisciplinary care and have higher mortality rates than other common cancers, such as breast and prostate cancer. Using Surveillance, Epidemiology, and End Results (SEER)–Medicare linked data from patients diagnosed with NSCLC or CRC in 2016-2017, we assembled patient-sharing networks to examine whether being treated by a linchpin oncologist was associated with risk of mortality following diagnosis.

Methods

Data source and study cohort

The SEER-Medicare database links SEER cancer registry demographic and tumor characteristics with Medicare claims for health services. Our study cohorts included patients diagnosed with incident CRC or NSCLC between January 1, 2016, and December 31, 2017. We excluded patients who were younger than 66 or older than 99 years of age at the time of diagnosis, had a missing or non-US residential zip code, or were not continuously enrolled in fee-for-service Medicare in the 12 months before diagnosis and until the sooner of death or 12 months following diagnosis (Supplementary Figures 1 and 2, available online). We excluded patients with a death date missing from the Medicare Beneficiary Summary File or whose death dates did not match between SEER and Medicare Beneficiary Summary File. Finally, we limited our study cohort to patients with American Joint Committee on Cancer (AJCC) stage I to III cancers because access to surgery, radiation therapy, and chemotherapy is expected to prolong survival for these patients. The study was approved by the institutional review board at Dartmouth College.

Network assembly

We identified the physicians who had encounters with the patients in our cohorts in the 3 months before and 12 months following their cancer diagnosis in the Medicare Carrier files. From these encounters, physicians were connected if they had encounters with common patients to form a "patient-sharing network." In this network, the relationships, or "edges," between physicians were quantified by the number of shared patients. We analyzed separate patient-sharing networks for patients with lung cancer and colorectal cancer. Physician age, sex, and specialty were identified from the Medicare Data on Provider Practice and Specialty (MD-PPAS) file. We identified physicians with specialties of medical oncology, radiation oncology, and surgery. For CRC surgeons, we included those with a specialty of surgical oncology and general surgery; for lung cancer surgeons, we included those with a specialty of thoracic surgery, surgical oncology, and general surgery.

Attribution of oncologists to patients

Because patients will typically encounter their oncologists after cancer diagnosis, we used a 90-day look-forward window starting on day 1 of their month of diagnosis to assign patients to a medical oncologist, radiation oncologist, or surgeon. Patients who had encounters with multiple oncologists of the same specialty type were assigned to the physician with whom they had the plurality of encounters within the 90-day time frame. This attribution approach is expected to capture the oncologists who were involved in treatment planning and initiation.

Independent variable of interest

The independent variable of interest in this study was oncologist linchpin score. The linchpin score was calculated for each oncologist in the lung cancer and CRC patient-sharing networks (12). In Figure 1, we demonstrate the linchpin score calculation for medical oncologist i (vertex v_i) by summing edges with peers who lack ties to other medical oncologists, and then dividing by the sum of all shared ties. In this example, medical oncologist i shares patients with 4 other physicians (vertices v_a, v_b, v_c, *and* v_d,), and the values along each edge represent the number of shared patients. Only 1 of those physicians (v_c) has an established tie with another medical oncologist. The linchpin score is calculated by summing the edges that medical oncologist i has with physicians who are not connected to another medical oncologist (in this example, vertices v_a, v_b, *and* v_d,), and then dividing by the sum of all edges. Each oncologist is assigned a score that ranges from 0 (eg, if all peers in Figure 1 shared patients with at least 1 other medical oncologist) to 1 (eg, if none of the peers in Figure 1 shared patients with another medical oncologist). We considered an oncologist to be a linchpin if the linchpin score was in the top 15% of the distribution of linchpin scores for their specialty; alternative thresholds were explored in sensitivity analyses.

Outcome variable

The primary outcome variable was overall survival in months within a 2-year follow-up observation period. Because of the 90-day look-forward window used to assign oncologists to patients, we started measuring a patient's survival time 3 calendar months after diagnosis and followed the patient through to their month of death or the end of follow-up. As a result, patients who survived less than 3 months after cancer diagnosis were not included in these analyses. Patients who were alive at the end of the 2-year follow-up period were censored.

Covariate measures

Patient age in years at diagnosis, sex, race, ethnicity, AJCC tumor stage, US Census Bureau tract-level poverty, county-level rurality, and SEER region were obtained from the SEER Cancer File. For patient race, we used the SEER Race Recode variable (White/Black/Other), where "Other" is inclusive of American Indian/Alaska Native and Asian/Pacific Islander. The Charlson Comorbidity Index was calculated using the 12 months of claims

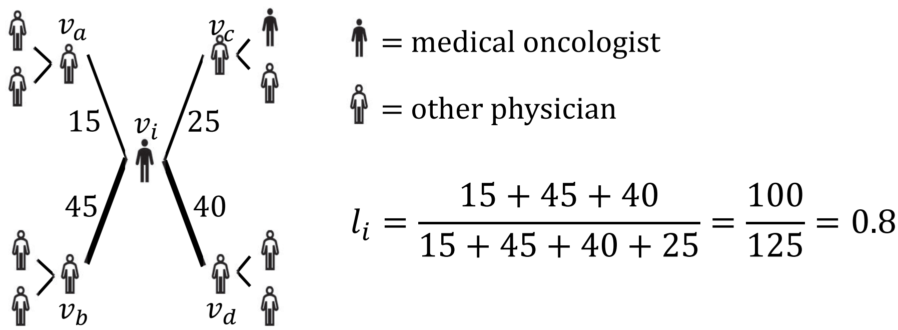

Figure 1. Illustration of linchpin score calculation. Numbers adjacent to edge lines represent shared patients.

preceding the month of cancer diagnosis (18). Poverty was measured using the Yost Index, which was developed using US-based quintiles of a composite socioeconomic status score from US Census tract-level American Community Survey 5-year estimates (19,20). We calculated node strength to determine the overall prominence, or centrality, of each oncologist in the network. Physician node strength is the sum of each physician's patient-sharing ties and is highly correlated with patient volume. We dichotomized node strength using a threshold of the lowest 15th percentile of node strength for each cancer specialty to capture the least connected oncologists in the patient-sharing networks. Physician age, sex, and practice setting (metropolitan vs nonmetropolitan) were obtained from the MD-PPAS file. SEER categorizes the geographic location of each physician in the dataset by core-based statistical areas, which denote metropolitan, micropolitan, and non–core-based statistical areas. We considered oncologists to practice in a metropolitan area if they were categorized as metropolitan; otherwise, they were categorized as nonmetropolitan.

Statistical analyses

We examined bivariate associations between oncologist characteristics and linchpin status using χ^2 and Wilcoxon rank sum tests for categorical and continuous variables, respectively. We assessed bivariate associations between being treated by a linchpin oncologist and patient race, ethnicity, rurality, and socioeconomic status using χ^2 tests. We estimated a series of Cox proportional hazards models to examine the associations between patient characteristics and oncologist linchpin score and survival for each cancer type. First, we estimated adjusted Cox proportional hazards models, including all patient characteristics (patient age in years at diagnosis, sex, race, ethnicity, AJCC stage, Charlson Comorbidity Index, US Census tract-level poverty, county-level rurality, and SEER region), oncologist rurality, and oncologist node strength. An indicator variable for whether the patient was assigned an oncologist of each specialty type was included to account for patients who did not see all 3 types of specialists. We then estimated the models, including oncologist linchpin score. We repeated the models with group frailty for patient county (the survival analysis analogy of a random effect in a mixed effect regression model) to better distinguish the effect of a linchpin from geographic location. Finally, we explored potential effect modification of oncologist rurality and oncologist node strength on associations between oncologist linchpin score and survival with interaction terms.

Table 1. Study cohort patient characteristics

Characteristic	Lung cancer n = 10 081	Colorectal cancer n = 9036
Age at diagnosis, No. (%), y		
66-69	1898 (18.8)	1607 (17.8)
70-74	2894 (28.7)	1907 (21.1)
75-79	2478 (24.6)	2022 (22.4)
80-84	1720 (17.1)	1718 (19.0)
≥85	1091 (10.8)	1782 (19.7)
Female sex, No. (%)	5126 (50.8)	4819 (53.3)
Race, No. (%)		
Black	729 (7.2)	609 (6.7)
White	8960 (88.9)	7949 (88.0)
Other	392 (3.9)	478 (5.3)
Hispanic ethnicity, No. (%)	348 (3.5)	541 (6.0)
American Joint Committee on Cancer stage, No. (%)		
I	5158 (51.2)	2346 (26.0)
II	1514 (15.0)	3483 (38.6)
III	3409 (33.8)	3207 (35.5)
Charlson Comorbidity Index, mean (SD)	2.05 (1.9)	1.52 (1.8)
Rurality, No. (%)		
Metropolitan	8262 (82.0)	7453 (82.5)
Nonmetropolitan	1819 (18.0)	1583 (17.5)
Yost Index quintile, No. (%)		
1 (lowest socioeconomic status)	1696 (16.8)	1398 (15.5)
2	1846 (18.3)	1537 (17.0)
3	1983 (19.7)	1791 (19.8)
4	2169 (21.5)	1965 (21.7)
5 (highest socioeconomic status)	2387 (23.7)	2345 (26.0)
Surveillance, Epidemiology, and End Results registry, No. (%)		
San Francisco-Oakland	328 (3.3)	351 (3.9)
Connecticut	553 (5.5)	445 (4.9)
Metropolitan Detroit	591 (5.9)	478 (5.3)
Iowa	626 (6.2)	694 (7.7)
New Mexico	162 (1.6)	209 (2.3)
Seattle (Puget Sound)	617 (6.1)	494 (5.5)
Utah	121 (1.2)	165 (1.8)
Metropolitan Atlanta	300 (3.0)	230 (2.5)
San Jose-Monterey	213 (2.1)	207 (2.3)
Los Angeles	440 (4.4)	550 (6.1)
Rural Georgia	21 (0.2)	25 (0.3)
Greater California	1858 (18.4)	1655 (18.3)
Kentucky	1098 (10.9)	730 (8.1)
Louisiana	693 (6.9)	636 (7.0)
New Jersey	1395 (13.8)	1398 (15.5)
Greater Georgia	1065 (10.6)	769 (8.5)

Results

Our study included patients with a lung or colorectal cancer diagnosis in 2016-2017 within 16 SEER regions (Table 1). Regarding race and ethinicity, of the 10 081 patients diagnosed with lung cancer, 729 (7.2%) were Black, 348 (3.5%) were Hispanic, and 8960 (88.9%) were White. Patients residing in metropolitan areas accounted for 82.0% of the cohort (n = 8262), and those residing in US Census tracts in the highest quintile for socioeconomic status accounted for 23.7% of the cohort (n = 2387) compared with 16.8% (n = 1696) residing in US Census tracts in the lowest socioeconomic status quintile. Similarly, of the 9036 patients diagnosed with CRC, 7949 (88.0%) were White, 609 (6.7%) were Black, and 541 (6.0%) were Hispanic. Patients residing in metropolitan areas accounted for 82.5% of the cohort (n = 7453), and those residing in US Census tracts in the highest quintile for socioeconomic status accounted for 26.0% of the cohort (n = 2345) compared with 15.5% (n = 1398) residing in US Census tracts in the lowest socioeconomic status quintile.

We next compared oncologists who were linchpins with those who were not by their centrality in the patient-sharing networks, here captured by node strength, their practice location, and their demographics (age and sex) (Table 2). Linchpin medical oncologists and radiation oncologists were more likely to be in the bottom 15% of node strength (ie, were more isolated) and were more likely to practice in a nonmetropolitan location than nonlinchpin comparison physicians in both the lung cancer and CRC patient-sharing networks. Linchpin surgeons were also less central in the networks than nonlinchpin surgeons ($P < .001$), but they were not statistically significantly more likely to practice in a nonmetropolitan area in either the lung or CRC patient-sharing network ($P = .454$ and $P = .164$, respectively). Radiation oncologists who were linchpins were marginally older for both lung and CRC treating physicians (median age, 51 vs 49 years $P = .014$, and median age, 55 vs 50 years, $P = .018$, respectively). Linchpin oncologists were slightly more likely to be male among lung cancer radiation oncologists ($P = .022$) and CRC surgeons ($P = .019$).

In bivariate analyses presented in Table 3, we found that patient race, ethnicity, rurality, and socioeconomic status were associated with the likelihood of being treated by a linchpin oncologist. Among the patients with NSCLC, 22.7% of nonmetropolitan patients (vs 12.3% of metropolitan patients, $P < .001$), and 17.8% of patients in the lowest socioeconomic status quintile (vs 10.2% of patients in the highest socioeconomic status quintile, $P < .001$) were treated by a linchpin medical oncologist; similar trends were observed for linchpin radiation oncologists. There were no statistically significant associations between patient race, ethnicity, rurality, or socioeconomic status and seeing a linchpin lung cancer surgeon. Among patients with CRC, 22.2% of nonmetropolitan (vs 12.2% of metropolitan, $P < .001$) and 17.9% of patients in the lowest socioeconomic status quintile (vs 8.7% of those in the highest socioeconomic status quintile, $P < .001$) were treated by a linchpin medical oncologist. Similar trends were observed for patients treated by linchpin radiation oncologists and linchpin surgeons. Non-White patients and Hispanic patients with CRC were also more likely to see linchpin radiation oncologists ($P = .009$ and $P = .046$, respectively) and linchpin surgeons ($P = .004$ and $P = .001$, respectively) than White patients with CRC.

We assessed the extent to which being treated by a linchpin oncologist was associated with survival in both patient cohorts (Table 4). The observed mortality was approximately 38%

Table 2. Characteristics of linchpin oncologists[a]

	Lung cancer			Colorectal cancer		
	Not a linchpin	Linchpin	P[b]	Not a linchpin	Linchpin	P[b]
Medical oncology						
Node strength, No. (%)			<.001			<.001
Connected (top 85%)	1513 (98.1)	281 (83.1)		1441 (96.3)	245 (78.3)	
Isolated (bottom 15%)	29 (1.9)	57 (16.9)		55 (3.7)	68 (21.7)	
Practice setting, No. (%)			<.001			<.001
Metropolitan	1461 (94.7)	291 (86.1)		1416 (94.7)	279 (89.1)	
Nonmetropolitan	81 (5.3)	47 (13.9)		80 (5.3)	34 (10.9)	
Age, median (IQR), y	49 (42-59)	50 (42-60)	.648	49 (42-59)	50 (41-60)	.399
Sex, No. (%)			.330			.371
Female	459 (29.8)	91 (26.9)		449 (30.0)	102 (32.8)	
Male	1083 (70.2)	247 (73.1)		1046 (70.0)	209 (67.2)	
Radiation oncology						
Node strength, No. (%)			<.001			<.001
Connected (top 85%)	812 (97.1)	120 (78.9)		430 (93.1)	74 (79.6)	
Isolated (bottom 15%)	24 (2.9)	32 (21.1)		32 (6.9)	19 (20.4)	
Practice setting, No. (%)			<.001			.011
Metropolitan	796 (95.2)	130 (85.5)		435 (94.2)	80 (86.0)	
Nonmetropolitan	40 (4.8)	22 (14.5)		27 (5.8)	13 (14.0)	
Age, median (IQR), y	49 (41-58)	51 (43-60)	.014	50 (42-58)	55 (43-60)	.018
Sex, No. (%)			.022			.419
Female	213 (25.5)	25 (16.4)		108 (23.4)	26 (28.0)	
Male	622 (74.5)	127 (83.6)		354 (76.6)	67 (72.0)	
Surgery						
Node strength, No. (%)			.004			<.001
Connected (top 85%)	748 (94.4)	108 (87.1)		1899 (93.4)	281 (69.6)	
Isolated (bottom 15%)	44 (5.6)	16 (12.9)		135 (6.6)	123 (30.4)	
Practice setting, No. (%)			.454			.164
Metropolitan	686 (86.6)	111 (89.5)		1800 (88.5)	347 (85.9)	
Nonmetropolitan	106 (13.4)	13 (10.5)		234 (11.5)	57 (14.1)	
Age, median (IQR), y	53 (45-60)	53 (47-60)	.549	51 (42-60)	53 (44-61)	.024
Sex, No. (%)			>.1			.019
Female	83 (10.5)	<11		311 (15.3)	43 (10.6)	
Male	710 (89.5)	>112		1722 (84.7)	361 (89.4)	

[a] Counts of physicians between 0 and 11 are suppressed to adhere to the data use agreement with the National Cancer Institute. IQR = interquartile range.
[b] P values were calculated using $\chi 2$ tests for categorical variables and Wilcoxon rank sum tests for continuous variables.

Table 3. Associations between patient race, ethnicity, rurality, and socioeconomic status and being treated by a linchpin oncologist

	Medical oncology			Radiation oncology			Surgery		
Characteristic	Not treated by linchpin, %	Treated by linchpin, %	P[a]	Not treated by linchpin, %	Treated by linchpin, %	P[a]	Not treated by linchpin, %	Treated by linchpin, %	P[a]
Lung cancer cohort	n = 5339	n = 882		n = 4218	n = 670		n = 3883	n = 346	
Race			.036			.202			.801
Black	85.3	14.7		86.1	13.9		92.9	7.1	
White	86.1	13.9		86.5	13.5		91.8	8.2	
Other	80.3	19.7		81.6	18.4		91.5	8.5	
Ethnicity			.127			.101			.077
Hispanic	82.2	17.8		81.8	18.2		87.8	12.2	
Non-Hispanic	85.9	14.1		86.4	13.6		92.0	8.0	
Rurality			<.001			<.001			.205
Metropolitan	87.7	12.3		88.2	11.8		92.1	7.9	
Nonmetropolitan	77.3	22.7		77.9	22.1		90.6	9.4	
Yost Index quintile			<.001			<.001			.482
1 (lowest socioeconomic status)	82.2	17.8		80.9	19.1		92.5	7.5	
2	82.5	17.5		82.1	17.9		91.7	8.3	
3	84.8	15.2		86.2	13.8		91.5	8.5	
4	88.2	11.8		88.8	11.2		90.6	9.4	
5 (highest socioeconomic status)	89.8	10.2		91.5	8.5		92.7	7.3	
Colorectal cancer cohort	n = 4724	n = 758		n = 898	n = 161		n = 6936	n = 918	
Race			.307			.009			.004
Black	83.7	16.3		76.2	23.8		83.7	16.3	
White	86.4	13.6		86.1	13.9		88.6	11.4	
Other	85.2	14.8		75.0	25.0		89.4	10.6	
Ethnicity			.079			.046			.001
Hispanic	82.9	17.1		76.7	23.3		83.4	16.6	
Non-Hispanic	86.4	13.6		85.4	14.6		88.6	11.4	
Rurality			<.001			.001			<.001
Metropolitan	87.8	12.2		86.5	13.5		89.1	10.9	
Nonmetropolitan	77.8	22.2		77.4	22.6		84.6	15.4	
Yost Index quintile			<.001			.001			<.001
1 (lowest socioeconomic status)	82.1	17.9		79.0	21.0		83.9	16.1	
2	82.3	17.7		77.8	22.2		87.6	12.4	
3	83.3	16.7		86.4	13.6		86.7	13.3	
4	88.2	11.8		90.6	9.4		90.2	9.8	
5 (highest socioeconomic status)	91.3	8.7		86.6	13.4		91.0	9.0	

[a] *P* values were calculated using χ^2 tests.

(n = 3778) for the NSCLC cohort and 19% (n = 1667) for the CRC cohort. For lung cancer, being treated by a linchpin medical oncologist or radiation oncologist was associated with worse survival. Of patients with NSCLC who saw a medical oncologist, those treated by a linchpin medical oncologist had a greater hazard of mortality (adjusted hazard ratio [HR] = 1.14, 95% confidence interval [CI] = 1.03 to 1.28, *P* = .015). Similar estimates were observed for linchpin radiation oncologists (adjusted HR = 1.17, 95% CI = 1.04 to 1.32, *P* = .011). For patients with CRC, the association of oncologist linchpin status with survival was greatest for surgeons. Of patients with CRC who saw a surgeon, patients treated by a linchpin surgeon had a greater hazard of mortality (adjusted HR = 1.22, 95% CI = 1.03 to 1.43, *P* = .018). These results were comparable when including group frailty for patient county. Sensitivity analyses exploring a range of alternative thresholds for linchpin score demonstrated that the strongest associations with mortality were typically for linchpin score thresholds between the 80th and 95th percentiles (Figure 2). The overall associations between physician node strength and rurality were not statistically significant, the exception being patients treated by a rural lung cancer surgeon, who had a greater hazard of mortality (adjusted HR = 1.27, 95% CI = 1.02 to 1.58, P = .034).

Finally, we used interaction terms to assess whether the effect of linchpin oncologists on patient outcomes depended on whether the oncologist practiced in a nonmetropolitan setting or were peripheral in the patient-sharing network, as captured by low node strength (Supplementary Table 1, available online). We found that risk of mortality among patients with NSCLC treated by a linchpin radiation oncologist is greater among nonmetropolitan (vs metropolitan) radiation oncologists (adjusted HR = 1.43, 95% CI = 1.03 to 1.98, *P* = .03). No other statistically significant interactions were observed between linchpin status and practice setting or node strength.

Discussion

We found that a network-based measure identifying linchpin oncologists, whose peers lack ties to other oncologists of the same specialty, was often associated with worse survival for patients diagnosed with nonmetastatic NSCLC or CRC in 2016-2017. The associations between linchpin oncologists and survival varied by cancer type and specialty, which may reflect differences in the centralization of care and organization of referral patterns across these dimensions. Examining the extent to which being treated by a linchpin oncologist is associated with clinical outcomes other than survival could uncover potential mechanisms underlying these observations. This work adds to theory-based research on utilization of health-care services from an ecological perspective, which posits that access to health-care resources is influenced by the spatial distribution of individual, environmental, and health system factors (21).

Table 4. Hazard ratios of mortality among patients with lung and colorectal cancer, with and without oncologist linchpin score[a]

Characteristic	Lung cancer adjusted hazard ratio (95% confidence interval) (3774 events/10 056 patients)		Colorectal cancer adjusted hazard ratio (95% confidence interval) (1667 events/8994 patients)	
	Model 1	Model 2 (with oncologist linchpin score)	Model 1	Model 2 (with oncologist linchpin score)
Rural	1.03 (0.93 to 1.14)	1.03 (0.93 to 1.14)	1.05 (0.89 to 1.24)	1.05 (0.89 to 1.25)
Hispanic	1.09 (0.92 to 1.3)	1.08 (0.91 to 1.29)	0.82 (0.65 to 1.03)	0.81 (0.64 to 1.02)
Race				
White	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)
Black	1.15 (1.02 to 1.3)[b]	1.15 (1.01 to 1.3)[b]	1.13 (0.93 to 1.37)	1.12 (0.92 to 1.36)
Other	0.79 (0.66 to 0.95)[b]	0.79 (0.66 to 0.95)[b]	0.89 (0.71 to 1.13)	0.90 (0.71 to 1.13)
Yost Index quintile				
1 (lowest socioeconomic status)	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)
2	0.98 (0.88 to 1.09)	0.98 (0.88 to 1.08)	1.02 (0.86 to 1.20)	1.03 (0.87 to 1.21)
3	0.91 (0.82 to 1.02)	0.91 (0.82 to 1.02)	0.88 (0.74 to 1.04)	0.88 (0.74 to 1.05)
4	0.89 (0.79 to 0.99)[b]	0.89 (0.79 to 1.00)[b]	0.92 (0.77 to 1.09)	0.92 (0.77 to 1.10)
5 (highest socioeconomic status)	0.80 (0.71 to 0.91)[d]	0.81 (0.71 to 0.91)[d]	0.77 (0.64 to 0.93)[c]	0.78 (0.64 to 0.93)[c]
Age group, y				
66-69	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)
70-74	1.16 (1.05 to 1.29)[c]	1.16 (1.05 to 1.29)[c]	1.03 (0.85 to 1.25)[d]	1.03 (0.85 to 1.26)[d]
75-79	1.32 (1.19 to 1.47)[d]	1.32 (1.19 to 1.47)[d]	1.46 (1.22 to 1.76)[d]	1.47 (1.22 to 1.76)[d]
80-84	1.52 (1.35 to 1.69)[d]	1.52 (1.36 to 1.7)[d]	2.03 (1.7 to 2.43)[d]	2.03 (1.70 to 2.43)[d]
≥85	2.10 (1.86 to 2.37)[d]	2.11 (1.87 to 2.38)[d]	3.07 (2.59 to 3.65)[d]	3.08 (2.59 to 3.66)[d]
Female sex	0.80 (0.75 to 0.86)[d]	0.80 (0.75 to 0.86)[d]	0.88 (0.8 to 0.97)[b]	0.88 (0.8 to 0.97)[b]
American Joint Committee on Cancer stage				
I	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)	1.00 (Referent)
II	1.98 (1.79 to 2.18)[d]	1.98 (1.79 to 2.18)[d]	1.26 (1.09 to 1.45)[c]	1.26 (1.09 to 1.45)[c]
III	2.73 (2.53 to 2.95)[d]	2.73 (2.53 to 2.95)[d]	2.32 (2.02 to 2.67)[d]	2.32 (2.02 to 2.67)[d]
Charlson Comorbidity Index score	1.12 (1.1 to 1.14)[d]	1.12 (1.1 to 1.14)[d]	1.19 (1.16 to 1.22)[d]	1.19 (1.16 to 1.22)
Rural medical oncologist	1.00 (0.83 to 1.2)	0.95 (0.79 to 1.15)	1.02 (0.77 to 1.36)	1.03 (0.77 to 1.37)
Rural radiation oncologist	1.18 (0.97 to 1.43)	1.16 (0.96 to 1.41)	1.16 (0.72 to 1.88)	1.20 (0.74 to 1.96)
Rural surgeon	1.28 (1.03 to 1.59)[b]	1.27 (1.02 to 1.58)[b]	1.14 (0.91 to 1.42)	1.13 (0.91 to 1.41)
Medical oncologist node strength, bottom 15%	1.15 (0.82 to 1.63)	1.06 (0.75 to 1.5)	1.15 (0.77 to 1.71)	1.15 (0.76 to 1.72)
Radiation oncologist node strength, bottom 15%	0.87 (0.58 to 1.3)	0.82 (0.55 to 1.23)	0.8 (0.42 to 1.51)	0.81 (0.43 to 1.54)
Surgeon node strength, bottom 15%	1.00 (0.58 to 1.74)	0.95 (0.55 to 1.66)	0.86 (0.61 to 1.2)	0.81 (0.57 to 1.13)
Linchpin medical oncologist	N/A	1.14 (1.03 to 1.28)[b]	N/A	0.94 (0.78 to 1.13)
Linchpin radiation oncologist	N/A	1.17 (1.04 to 1.32)[b]	N/A	0.93 (0.63 to 1.36)
Linchpin surgeon	N/A	1.1 (0.9 to 1.35)	N/A	1.22 (1.03 to 1.43)[b]

[a] Model also included fixed effects for Surveillance, Epidemiology, and End Results registry and whether the patient saw a medical oncologist, radiation oncologist, or surgeon. N/A = not applicable.
[b] $P < .05$; [c] $P < .01$; [d] $P < .001$.

We found that linchpin oncologists (vs nonlinchpin oncologists) were more likely to practice in nonmetropolitan settings, were slightly older, and were peripheral in the network. We also found that linchpin oncologists were more likely to treat patients who were from minority racial and ethnic groups, resided in rural areas, and were socioeconomically disadvantaged, supporting the notion that linchpin status of oncologists may be indicative of limited access to multidisciplinary care because of geographic or other barriers. Our work adds to studies that found that patients with cancer living in areas characterized by lower oncologist density experienced worse outcomes (8,9). Our findings also extend prior work investigating associations between oncologist characteristics and outcomes for patients with cancer, which have often examined surgeon case volume, specialization, experience, and rurality (22,23). It is possible that patient-sharing networks measures, such as linchpin score, interact with practice rurality as well as other oncologist and workforce measures to associate with patient outcomes by varying amounts, depending on their combined levels (eg, the association involving 1 of these variables varies across levels of the other variables). Our study found that nonmetropolitan practice setting can influence the association between linchpin oncologists and patient outcomes. Future work examining factors associated with being a linchpin oncologist in different settings may lead to refinement in how linchpin oncologists are defined (eg, because of scarcity vs other reasons) and a more nuanced understanding of the causes and consequences of oncologists becoming locally unique in their networks.

Our approach—using network analysis to understand access to cancer specialists—has several strengths over existing approaches. Oncologist density is an established measure of the oncology workforce and is often calculated within small areas, such as counties or hospital service areas. Many sparsely populated areas often have no oncologists, however, which is understandable because the alternative would likely lead to oversupply and inefficiency. To address these limitations and innovate how the oncology workforce is measured, linchpin score examines the patient-sharing ties for each physician across a patient-sharing network that is not constrained by small areas. Advantages to our network-based approach for measuring access to care are 1) linchpin score does not require partitioning patients and physicians into specific geographic units, which may not reflect referral patterns nor resources available in neighboring geographic units, and 2) linchpin score does not depend on the geographic units

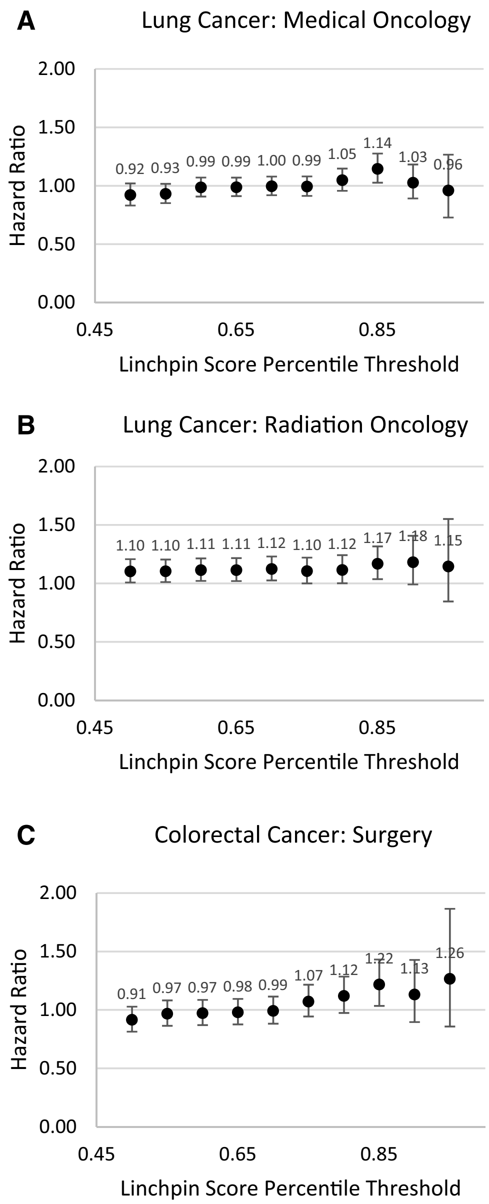

Figure 2. Sensitivity analyses for a range of linchpin score thresholds for **A**) lung cancer medical oncologists, **B**) lung cancer radiation oncologists, and **C**) colorectal cancer surgeons.

being perfectly nested within the geographic region represented in the data, which may not be feasible in all data sources.

Our study has several limitations, as well. First, our data were limited to fee-for-service Medicare beneficiaries aged 66 years and older in SEER regions, and our results may not generalize to other populations. Second, we are unable to observe all patient-sharing relationships among physicians, but considering that the median age at diagnosis for lung cancer is 71 years and for CRC is 67 years, our patient-sharing networks likely captured most oncologists involved in treating patients with these cancers and the relationships among them. Third, fee-for-service Medicare is characterized by relatively few administrative constraints on access to health-care professionals compared with private insurance and the Medicare Advantage program, suggesting that physician linchpin scores could have greater implications within different coverage settings (eg, settings characterized by more "narrow networks") (24). Fourth, we were limited to studying a shorter-term survival outcome with the years of data obtained for this study; however, analyses presented both here and in the Supplementary Material (available online) accounted for censoring by the end of follow-up. Fifth, unobserved confounding from unmeasured patient and physician factors is a limitation of this work because of the observational study design. Sixth, the 3 out of 6 associations between linchpin status and mortality that were statistically significant at $P < .05$ do not remain statistically significant after adjusting for multiplicity. Finally, there is no established threshold by which an oncologist should be considered a linchpin; however, in sensitivity analyses, we considered a range of thresholds, and the strongest associations with survival time tended to occur when linchpins were defined as being within the top 10th to 20th percentiles of linchpin scores for their specialty. This finding suggests that there may be a point toward the upper end of the distribution of linchpin scores that leads to associations with worse outcomes because of particularly sparse patient-sharing networks that is not observed at lower ranges of the distribution.

In conclusion, our findings have important implications for health-care professionals and policymakers working to address anticipated workforce shortages in cancer care. Our investigation of a novel physician-level network measure found that oncologist linchpin score was often associated with worse survival among patients diagnosed with nonmetastatic NSCLC or CRC. Nationwide or regional coordinated efforts to address uneven geographic distributions of specialty care through creating referral pattern guidelines could use network analysis to identify areas particularly vulnerable to workforce shortages or other barriers related to access to multidisciplinary cancer care. For example, in New Zealand, a national gynecologic cancer steering group oversees care coordination and hub-and-spoke referral guidelines to facilitate connections between major comprehensive cancer centers and smaller satellite hospitals (25). Overall, our results suggest that efforts to improve cancer health outcomes through increasing access to cancer care would benefit from considering the underlying structure of patient-sharing networks to ensure that efforts are focused on health systems and physicians practicing in more vulnerable networks.

Data availability

The SEER-Medicare linked data underlying this article cannot be shared because of provisions outlined in the Data Use Agreement between the study principal investigator (E.L.M.) and the National Cancer Institute. Researchers interested in obtaining these data can submit a project-specific data request to the National Cancer Institute.

Author contributions

Erika L Moen, PhD, MS (Conceptualization; Data curation; Funding acquisition; Methodology; Project administration; Supervision; Writing—original draft), Rachel O. Schmidt, MS (Formal analysis; Methodology; Writing—review & editing), Tracy Onega, PhD, MPAS, MS (Conceptualization; Methodology; Writing—review & editing), Gabriel A. Brooks, MD (Conceptualization; Methodology; Writing—review & editing), A. James O'Malley, PhD (Conceptualization; Methodology; Writing—review & editing).

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Conflicts of interest

The authors report no conflicts of interest.

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