


## RESEARCH ARTICLE

# Physician network position and patient outcomes following implantable cardioverter defibrillator therapy

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**Objective:** To evaluate two novel measures of physician network centrality and their associations with implantable cardioverter defibrillator (ICD) procedure volume and health outcomes.

**Data Sources:** Medicare claims and the National Cardiovascular Data Registry data from 2007 to 2011.

**Study Design:** We constructed a national cardiovascular disease patient-sharing physician network and used network analysis to characterize physician network centrality with two measures: within-hospital degree centrality (number of connections within a hospital) and across-hospital degree centrality (number of connections across hospitals). The primary outcome was risk-adjusted 2-year case fatality. Hierarchical logistic regression estimated the effects of physician's within-hospital and across-hospital degree centrality on case fatality. We included 105 109 ICD therapy patients and 3474 ICD implanting physicians in our analyses.

**Principal Findings:** After controlling for other physician and hospital characteristics, we observed greater risk-adjusted case fatality among patients treated by physicians in the highest across-hospital degree tertile compared to lowest tertile (OR [95% CI] = 1.10 [1.04-1.16],  $P = 0.001$ ) and lowest tertile volume physicians compared with highest volume (OR [95% CI] = 0.90 [0.84-0.95],  $P < 0.001$ ). Physician's within-hospital degree tertile was inversely associated with case fatality but not statistically significant.

**Conclusions:** Degree centrality measures capture information independent of procedure volume and raise questions about the quality of physicians with networks that predict worse health outcomes.

## KEYWORDS

case fatality, degree centrality, implantable cardioverter defibrillator, physician network

## 1 | INTRODUCTION

An inverse association between patient mortality and surgeon and hospital procedure volume is one of the strongest empirical regularities in health services research.<sup>1-4</sup> These findings suggest that patients may improve their chances of survival by seeking treatment from high-volume surgeons within high-volume hospitals. If patients

are channeled to high-volume surgeons for selected surgical procedures,<sup>5</sup> it follows that these surgeons would become central within the patient-sharing patterns of a health system. This raises the question of whether established patient-sharing patterns may be related to surgeon procedure volume and predictive of patient outcomes. Using network analysis, we can quantify a physician's centrality within a "physician network" where ties exist between physicians

who share patients. Physician pairs who share patients are more likely to be familiar with and refer patients to each other.<sup>6</sup> The extent to which the network centrality of a surgeon is related to procedure volume and patient outcomes has not been studied.

We evaluate degree centrality to capture central physicians in a cardiovascular disease patient-sharing network based on the number of ties to other physicians. Recognizing that patient-sharing patterns within hospitals are likely established through different mechanisms than patient-sharing patterns across hospitals, and that a physician may be central (have many ties) within the hospital network but few ties across hospitals or vice versa, we evaluate both “within-hospital” and “across-hospital” degree centrality measures. Patient-sharing network edges among physicians attributed to the same hospital would contribute to their within-hospital degree, whereas patient-sharing network edges among physicians attributed to different hospitals would contribute to their across-hospital degree. While previous studies have characterized the connectedness of physicians (either individually or by specialty) within a hospital or hospital referral region,<sup>7-10</sup> this is the first study to examine structurally distinct measures of network position within and across hospitals using the national physician network and their associations with patient outcomes. Teasing apart the relationships between physician's within-hospital and across-hospital degree centrality, procedure volume, and patient outcomes will have implications for volume-based referral initiatives.<sup>11</sup>

This paper explores whether patients treated for implantable cardioverter defibrillator (ICD) therapy by physicians who are high volume and central in the patient-sharing network experience the best outcomes. Inverse associations between physician and hospital ICD procedure volume and adverse events associated with the procedure have been reported,<sup>12-14</sup> indicating that patients may indeed benefit from selective referrals to high-volume ICD providers. Patients may have better outcomes following ICD therapy because the implanting physician is more technically skilled, leading to fewer complications related to the procedure, or because the physician is adept at selecting patients who are most likely to benefit from the treatment, leading to improved long-term outcomes. Furthermore, it is not uncommon for patients to be referred across hospitals for ICD therapy,<sup>15</sup> suggesting that within-hospital and across-hospital patient-sharing patterns are potential referral pathways for this procedure. In the present analyses, we evaluate the relationships between physician's within-hospital and across-hospital degree centrality, procedure volume, and patient outcomes following ICD therapy: a longer-term outcome of 2-year case fatality and a combined shorter-term outcome of 30-day complications related to the procedure and 90-day case fatality.

## 2 | METHODS

### 2.1 | Overview of data and subjects

We obtained Medicare Provider Analysis and Review (MedPAR), Outpatient, and Carrier files from the Center for Medicare and

Medicaid Services (CMS) for years 2007-2011. Using appropriate diagnosis codes from the International Classification of Diseases, Ninth Revision (ICD-9), we identified cardiovascular patients who had two or more visits for any of the following diagnoses: arrhythmia, congestive heart failure, coronary heart disease, or peripheral vascular disease. Patients were required to be at least 65 years of age, have full Part A and B coverage (12 months or until death), and not be enrolled in Medicare Advantage.

Medicare beneficiaries were identified as receiving ICD therapy in the National Cardiovascular Data Registry (NCDR) ICD Registry. The ICD Registry is a CMS-mandated hospital registry for the inpatient setting that aimed to establish a national standard for understanding treatment patterns, quality, and outcomes for ICD therapy patients. The ICD Registry database contains numerous demographic variables and clinical risk factors used in the risk adjustment.

Doximity, Inc (<https://www.doximity.com/>), is a professional network site for health care professionals in the United States, with over 70 percent of US physicians as verified members, and was used to obtain additional physician characteristics. Doximity data have been used and verified in previous studies.<sup>16,17</sup> The American Hospital Association (AHA) and MedPAR and Provider of Services data downloaded from CMS provided hospital characteristics. The 2010 Census ZIP code-level data were used to calculate socioeconomic indicators. The institutional review board of Geisel School of Medicine at Dartmouth approved the study protocol.

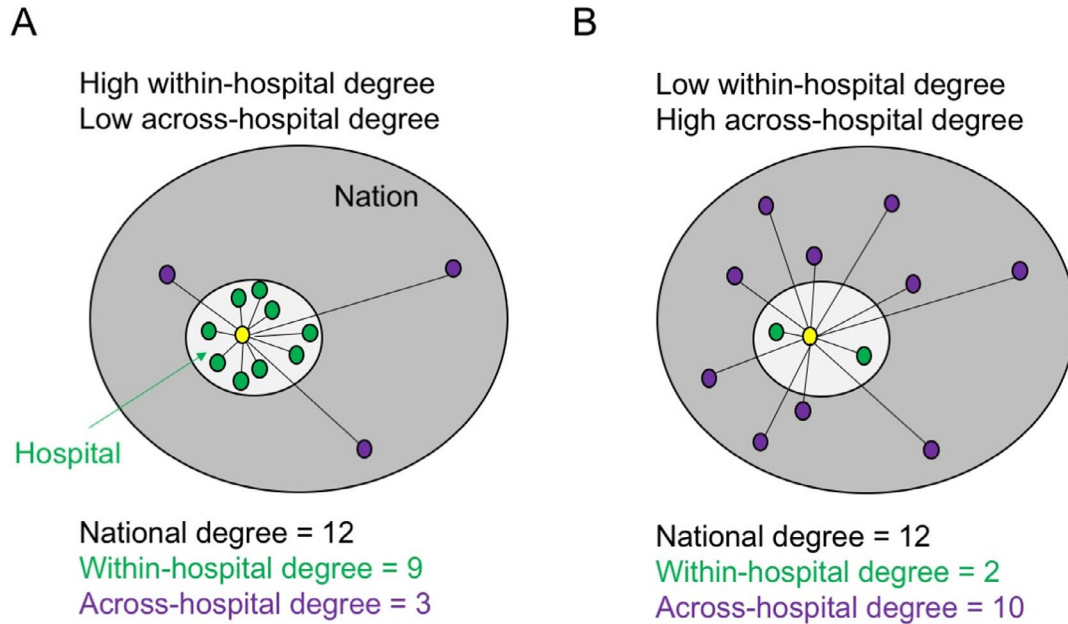
### 2.2 | Attribution of physicians to hospitals

Physicians were empirically attributed to hospitals using the physician-hospital network methodology developed previously.<sup>18</sup> The attribution was based on the hospital where he/she submitted the most Medicare inpatient claims or, if they did not submit inpatient service claims, they were attributed to the hospital at which the plurality of their patients was admitted.

### 2.3 | Physician network analysis

We identified clinical encounters between cardiovascular disease patients and physicians using Medicare Evaluation and Management claims related to cardiac care from the Medicare Physician/Supplier Part B claims during the study period. Links between physicians were created if the physicians shared at least one patient within the same calendar year to create a “physician network.”

Using national Medicare claims, physician networks can be inclusive of the entire nation<sup>19</sup> or bounded using previously developed algorithms to assign physicians to “groups” (eg, hospitals or hospital referral regions).<sup>15,20</sup> Degree centrality is a measure of the number of ties a physician has to other physicians within the network boundary. A mathematically appealing feature of degree centrality is that it perfectly partitions into the sum of the measure evaluated for a subnetwork and on the complement of the subnetwork. Relevant to this example, a physician's national degree equals the sum of ties within the hospital and the ties across hospitals (Figure 1). Here, for



**FIGURE 1** Illustration of within-hospital and across-hospital degree. Nodes (circles) represent physicians, and lines represent relationships between physicians. Focal physician for which degree is measured is colored yellow. A, Illustration of a physician with high within-hospital degree and low across-hospital degree. B, Illustration of a physician with low within-hospital degree and high across-hospital degree [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

each physician we calculate a “within-hospital” degree centrality (number of ties a physician has to other physicians attributed to the same hospital) and “across-hospital” degree centrality (number of ties a physician has to other physicians across hospitals). Therefore, the network edges are considered as being a “within-hospital” edge or an “across-hospital” edge without losing any information with respect to the physician’s degree. Tertiles of within-hospital and across-hospital degree of physicians were calculated and categorized as “low,” “medium,” and “high” degree. Degree centrality was calculated using the *igraph* package<sup>21</sup> in R.<sup>22</sup>

## 2.4 | Study variables

The ICD Registry was used to determine the following demographic and disease severity risk-adjustment variables: patient age, sex, race, ventricular tachycardia, New York Heart Association symptom class, left ventricular ejection fraction during admission, ischemic heart disease, nonischemic dilated cardiomyopathy, heart failure, duration of symptoms since initial onset, prior myocardial infarction, previous ICD therapy, coronary artery bypass grafting during admission or previously, percutaneous coronary intervention during admission or previously, and family history of sudden death. Additional patient-level covariates were whether the patient met ICD therapy clinical guidelines,<sup>15</sup> socioeconomic indicators of patient ZIP code, and travel distance between patient ZIP code and ICD hospital. Travel distances from each ZIP code to each regional hospital (ie, American Hospital Association (AHA) hospital centroid) were estimated with ArcGIS software using U.S. street-level road network geographic data between all 2010 ZIP code-weighted centroids (origins) and all

2010 AHA hospitals (destinations) within an 8-hour (480-minute) cutoff time. We linked these data to the Medicare beneficiaries who received ICD therapy using the patient’s ZIP code and the ICD surgery hospital, obtained from the NCDR ICD Registry.

Implantable cardioverter defibrillator procedure volume was measured as the number of ICD procedures that each physician performed on Medicare patients each year. We obtained data on specialty, publications, and clinical trial participation from Doximity. Specialty was categorized as “Cardiology” or “other,” with “other” primarily including thoracic surgery. Binary indicators for whether the physician ever published or ever participated in clinical trials were measured to identify physicians who may be prominent in academic research (publications) or clinical settings (clinical trials).

We also evaluated several hospital characteristics: annual hospital ICD procedure volume, teaching status, a measure of hospital market concentration, the Herfindahl-Hirschman Index (HHI), and hospital degree centrality. Hospital procedure volume was characterized as the number of ICD procedures that each hospital performed on Medicare patients each year. Teaching status of hospitals was obtained from the American Hospital Association (AHA) and MedPAR and Provider of Services data downloaded from CMS. The hospital-level HHI was calculated as previously described and represents local market competition normalized so that 1 indicates a monopoly and values approaching zero indicate a perfectly competitive market.<sup>23</sup> To adjust for ICD hospital network prominence, we aggregated the physician ties by hospital affiliation to calculate a hospital-level degree centrality measure equal to the number of ties a hospital has to other hospitals in the nation.<sup>15</sup>

**TABLE 1** Characteristics of patients, ICD implanting physicians, and hospitals according to physician's within-hospital and across-hospital degree

Characteristics	Within-hospital degree			Across-hospital degree			P-value*	P-value*
	Low (1-74)	Medium (75-114)	High (115-448)	Low (1-186)	Medium (187-308)	High (308-1055)		
ICD patients, n	25 488	34 414	42 189	23 816	35 263	45 989	<0.001	<0.001
Age in years, median (1st, 3rd q)	73 (67, 79)	73 (67, 79)	73 (67, 79)	73 (67, 79)	73 (67, 79)	73 (67, 79)	n.s.	n.s.
Male, %	72	72	72	73	73	72	n.s.	n.s.
Race								
White, %	83	86	84	86	86	82	<0.001	<0.001
Black, %	11	11	13	10	10	14		
Other, %	6	3	3	4	4	4		
Travel distance to ICD hospital in miles, mean (SD)	33 (48)	32 (46)	32 (45)	32 (49)	32 (45)	32 (46)	0.05	n.s.
ICD physician (n = 3474)								
ICD procedure volume per year, mean (SD)	15 (n.r.)	19 (n.r.)	24 (n.r.)	19 (n.r.)	27 (15)	37 (21)	<0.001	<0.001
Specialty: cardiology, %	77	89	94	74	92	98	<0.001	<0.001
Publishing record, %	53	56	59	58	55	54	0.001	0.02
Participates in clinical trials, %	15	20	22	19	17	22	<0.001	<0.001
ICD hospital (n = 1280)								
Hospital volume per year, mean (SD)	49 (n.r.)	59 (n.r.)	87 (64)	59 (n.r.)	61 (n.r.)	70 (n.r.)	<0.001	<0.001
Teaching hospital, %	16	20	33	27	21	21	<0.001	<0.001
Hospital degree, mean (SD)	484 (278)	570 (313)	734 (374)	546 (332)	563 (299)	687 (370)	<0.001	<0.001
Hospital HHI, mean (SD)	0.17 (0.14)	0.19 (0.15)	0.22 (0.15)	0.25 (0.18)	0.21 (0.14)	0.15 (0.12)	<0.001	<0.001

Note. The range for each degree tertile is included in parentheses underneath the column headers. n.r., indicates that the standard deviation for procedure volume was not reported due to CMS data suppression policies; n.s., nonsignificant (P-value > 0.05); q, quartile; SD, standard deviation. \*p-values were calculated using two-way ANOVA tests and Pearson's chi-squared tests.

## 2.5 | Assessment of outcome

The primary outcome variable of interest was the binary indicator of whether the patient died within the 2 years following ICD therapy. The expected value of the outcome thus expresses the relationship between the predictors and 2-year case fatality (probability of death). The secondary outcome of interest was a combined indicator of shorter-term adverse outcomes following ICD therapy: 30-day complications related to the procedure and 90-day case fatality. The ICD patient was assigned to the ICD implanting physician who performed the procedure based on the unique National Provider Identifier (NPI) on the Part B Medicare fee-for-service administrative claims data for the ICD implantation encounter.

## 2.6 | Statistical analyses

Descriptive statistics and bivariate analyses were used to evaluate the associations between within-hospital and across-hospital degree and other study variables. The effects of ICD implanting physician's within-hospital and across-hospital degree centrality measures on ICD therapy patient outcomes were estimated using hierarchical multivariable logistic regression of the binary indicator of whether the patient experienced the adverse event as the dependent variable. In addition to the degree and volume variables of primary interest, year of surgery and various other variables (eg, disease severity) that could confound the relationship if not controlled were included as predictors. To help guard against reverse causality, patient outcomes were evaluated in year  $t + 1$  while the network and volume predictors were evaluated in year  $t$ . Random effects were specified to account for clustering of patients by physician, hospital, and HRR. Thus, the model has the form:

$$\begin{aligned} \Pr (y_{ijkl} = 1 | \theta_j, \delta_k, \gamma_l, \text{Year}_{ijkl} = t + 1) \\ = \text{logit}^{-1}(\beta_0 + \beta_1 \text{Pat}_{ijkl} + \beta_2 \text{Phys}_{jkl} + \beta_3 \text{Hosp}_{kl} + \theta_j + \delta_k + \gamma_l) \end{aligned}$$

$$\theta_j \sim \text{Normal}(0, \tau^2); \delta_k \sim \text{Normal}(0, \alpha^2); \gamma_l \sim \text{Normal}(0, \sigma^2),$$

where  $Y_{ijkl}$  is a binary indicator of the health outcome for patient  $i$  who received surgery from physician  $j$  at hospital  $k$  in HRR  $l$ . Patient-level covariates are depicted by  $Pat$  (including dummy variables for each level of  $\text{Year}_{ijkl}$ ), the predictors particular to a given physician are depicted by  $Phys$ , and the descriptors of the hospital are depicted by  $Hosp$ . Random effects for physician, hospital, and HRR are depicted as  $\theta_j$ ,  $\delta_k$ , and  $\gamma_l$ , respectively. In extensions of the above model, we tested whether the associations between the health outcome and the ICD implanting physician's within-hospital and across-hospital degree differed by physician procedure volume by including interaction terms in the multivariable logistic regression. Statistical analyses were performed using the lme4 package<sup>24</sup> in the R statistical software.

## 3 | RESULTS

Between 2008 and 2011, 246 951 Medicare beneficiaries with congestive heart failure received ICD therapy, and of those, 195 174 were enrolled in Parts A and B for 12 months and not enrolled in Medicare Advantage. We excluded patients who were missing data on their implanting physician or hospital ( $n = 89\,068$ ) or whose implanting physician was not included in the physician network ( $n = 997$ ), resulting in 105 109 ICD therapy patients included in our study. These patients were treated by 3474 implanting physicians (primarily electrophysiologist cardiologists and thoracic surgeons) within 1280 hospitals. The average number of procedures per physician per year was 20 (maximum = 142), and the average number of procedures per hospital was 44 (maximum = 395). Patient, physician, and hospital characteristics stratified by physician's within-hospital and across-hospital degree tertiles are shown in Table 1.

When assessed as continuous variables, within-hospital and across-hospital degree were moderately positively correlated with each other (Spearman's  $\rho = 0.25$ ). The implanting physician's within-hospital degree was positively associated with ICD procedure volume ( $\rho = 0.23$ ) and hospital ICD volume ( $\rho = 0.30$ ). The implanting physician's across-hospital degree was more strongly correlated with physician volume compared with hospital volume ( $\rho = 0.39$  and  $0.07$ , respectively). We next evaluated within-hospital and across-hospital degree by tertiles. The number of ICD implanting physicians within each within-hospital tertile stratified by each across-hospital degree tertile is shown in Table S1. Implanting physicians in the highest tertile for within-hospital degree were more likely to specialize in cardiology (vs other,  $P < 0.001$ ), publish ( $P = 0.001$ ), participate in clinical trials ( $P < 0.001$ ), practice at a teaching hospital ( $P < 0.001$ ) and a high-degree hospital ( $P < 0.001$ ), and be attributed to a hospital with greater market concentration ( $P < 0.001$ ) compared to implanting physicians in the lowest tertile for within-hospital degree (Table 1). Implanting physicians in the highest tertile for across-hospital degree were also more likely to specialize in cardiology ( $P < 0.001$ ), participate in clinical trials ( $P < 0.001$ ), and practice at a high-degree hospital compared to those in the lowest tertile (Table 1); however, implanting physicians with greater across-hospital degree were less likely to have published ( $P = 0.02$ ) and less likely to practice at teaching hospitals ( $P < 0.001$ ) or hospitals with greater market concentration ( $P < 0.001$ ; Table 1).

We next evaluated whether physician's within-hospital and across-hospital degree were related to the likelihood a patient experienced 2-year case fatality following ICD therapy ( $n = 24\,728$ ). The full estimated model of risk-adjusted 2-year case fatality following ICD therapy is presented in Table 2. Implanting physician's within-hospital degree was negatively associated with 2-year case fatality ( $P = 0.04$ ), whereas across-hospital degree was positively associated with 2-year case fatality ( $P < 0.001$ ; Table 2). When degree measures were treated as categorical variables (tertiles), case fatality among patients treated by physicians in the highest within-hospital degree tertile was lower, but not significantly different, compared with those treated by physicians in the lowest within-hospital degree

**TABLE 2** Estimated effects on risk-adjusted 2-y case fatality following ICD therapy

Characteristic	Estimate (SE)	P-value
<b>Physician variables</b>		
Within-hospital degree	-4.94e-4 (2.35e-4)	0.04
Across-hospital degree	2.91e-4 (7.56e-5)	<0.001
ICD procedure volume	-1.46e-3 (5.47e-4)	0.008
Specialty: cardiology	-2.39e-1 (4.93e-2)	<0.001
Publishing record	-2.94e-2 (2.05e-2)	0.15
Clinical trial participation	-6.88e-2 (2.45e-2)	0.005
<b>Hospital variables</b>		
ICD procedure volume	-4.05e-4 (2.34e-4)	0.08
Degree	3.51e-5 (3.91e-5)	0.37
HHI	1.35e-1 (8.30e-2)	0.10
Teaching status	-2.29e-2 (2.95e-2)	0.44
<b>Patient risk-adjustment variables</b>		
Age	2.78e-2 (9.35e-4)	<0.001
Female	-9.79e-2 (1.90e-2)	<0.001
<b>Race</b>		
White	-6.58e-2 (2.41e-1)	0.78
Black	1.33e-1 (2.42e-1)	0.58
Median income of ZIP code	-1.51e-6 (7.94e-7)	0.06
% living below poverty line of ZIP code	5.41e-1 (1.57e-1)	<0.001
Within ICD guidelines	-3.16e-1 (4.11e-2)	<0.001
Travel distance to ICD hospital (mi)	-9.39e-4 (2.02e-4)	<0.001
<b>Ventricular tachycardia</b>		
No	Referent	Referent
Yes, nonsustained	3.39e-1 (1.91e-2)	<0.001
Yes, monomorphic sustained	4.33e-1 (3.74e-2)	<0.001
Yes, polymorphic sustained	5.35e-1 (7.45e-2)	<0.001
<b>NYHA symptom class</b>		
Class 1	Referent	Referent
Class 2	2.98e-1 (6.08e-2)	<0.001
Class 3	6.98e-1 (6.02e-2)	<0.001
Class 4	1.05 (5.87e-2)	<0.001
<b>Duration of symptoms since heart failure onset</b>		
<3 mo	Referent	Referent
3-9 mo	-1.64e-1 (3.31e-2)	<0.001
>9 mo	1.61e-2 (2.53e-2)	0.53
LVEF during admission	-2.05e-2 (1.19e-3)	<0.001
CABG during admission	-2.74e-1 (9.60e-2)	0.004
PCI during admission	2.48e-1 (5.29e-2)	<0.001
<b>Previous ICD</b>		
No	Referent	Referent
Yes, single chamber	2.71e-1 (2.96e-2)	<0.001
Yes, dual chamber	1.35e-1 (4.12e-2)	0.001
Yes, biventricular	4.08e-1 (4.60e-2)	<0.001

(Continues)

TABLE 2 (Continued)

Characteristic	Estimate (SE)	P-value
NIDCM		
No	Referent	Referent
Yes, within past 3 mo	-2.24e-1 (3.43e-2)	<0.001
Yes, 3-9 mo	-3.27e-1 (6.58e-2)	<0.001
Yes, >9 mo	-1.69e-1 (3.68e-2)	<0.001
Ischemic heart disease		
No	Referent	Referent
Yes, at least one epicardial artery greater than 70% obstruction	1.15e-1 (3.27e-2)	<0.001
Yes, other	2.20e-1 (4.92e-2)	<0.001
Prior MI		
No	Referent	Referent
Yes, within 40 d of ICD implant	1.01e-1 (2.60e-2)	<0.001
Yes, greater than 40 d	-8.04e-3 (2.48e-2)	0.75
Yes, both within 40 d and >40 d	2.24e-1 (6.25e-2)	<0.001
Prior CABG	8.38e-2 (1.95e-2)	<0.001
Prior PCI		
No	Referent	Referent
Yes, within 3 mo	-1.13e-1 (2.51e-2)	<0.001
Yes, >3 mo	-6.97e-2 (2.46e-2)	0.005
Family history of sudden death	-1.22e-1 (4.74e-2)	0.010
Year of surgery		
2008	Referent	Referent
2009	2.22e-2 (2.42e-2)	0.36
2010	-6.75e-3 (2.83e-2)	0.81
2011	6.74e-3 (3.29e-2)	0.84

Note. The estimates and standard errors are presented using the shorthand for exponential notation (ie, e-2 indicates  $\times 10^{-2}$ ).

CABG, coronary artery bypass grafting; HHI, Herfindahl-Hirschman Index; LVEF, left ventricular ejection fraction; MI, myocardial infarction; NIDCM, nonischemic dilated cardiomyopathy; NYHA, New York Heart Association; PCI, percutaneous coronary intervention.

tertile (OR = 0.96 [0.91-1.01],  $P > 0.05$ ). Conversely, case fatality of patients treated by physicians in the highest across-hospital degree tertile was greater compared with patients treated by physicians in the lowest across-hospital degree tertile (OR = 1.10 [1.04-1.16],  $P < 0.001$ ).

To explore associations between physician's within-hospital and across-hospital degree, procedure volume, and short-term adverse outcomes, we analyzed a combined indicator of 30-day complications related to the procedure ( $n = 18\,294$ ) and 90-day case fatality ( $n = 4\,669$ ). The trends of the associations between physician's within-hospital and across-hospital degree with short-term adverse events remained (negative and positive, respectively), although they were no longer statistically significant (Table S2). Physician ICD procedure volume was also significantly negatively associated with short-term adverse events ( $P = 0.02$ ; Table S2).

Next, we evaluated whether the ICD procedure volume-outcome relationships were affected by the inclusion of implanting physician's within-hospital and across-hospital degree. In the full model including within-hospital and across-hospital degree, the patients had better

2-year outcomes when treated by a high-volume physician (top tertile compared to bottom tertile, OR = 0.90 [0.84-0.95],  $P < 0.001$ ; Table S3); hospital volume was not statistically significant (top tertile compared to bottom tertile, OR = 0.97 [0.91-1.03],  $P > 0.05$ ). When within-hospital and across-hospital physician degree were excluded, the effect of physician procedure volume on case fatality was slightly attenuated (OR = 0.92 [0.87-0.97],  $P = 0.004$ ), and the effect of hospital procedure volume on case fatality was unchanged (OR = 0.95 [0.89-1.01],  $P > 0.05$ ; Table S3).

To further characterize how implanting physician degree and volume are related to patient outcomes, we tested for significant interactions between physician's within-hospital and across-hospital degree and physician procedure volume (Table 3). The estimate of the interaction effect indicates that the association between within-hospital degree and case fatality decreased as physician procedure volume increased (est (SE) =  $1.49 \times 10^{-5}$  ( $7.13 \times 10^{-6}$ ),  $P = 0.04$ ); that is, the association between within-hospital degree and case fatality decreased by  $1.49 \times 10^{-5}$  for every ICD procedure performed. On the other hand, the effect of across-hospital degree on case

**TABLE 3** Estimation of interaction effects between implanting physician's within-hospital and across-hospital degree and procedure volume on predicting 2-y case fatality with multivariable logistic regression

Interaction model	Estimate (SE)	P-value	Interpretation
Within-hospital degree × physician volume	1.49e-05 (7.13e-06)	0.04	Within-hospital degree effect decreases as volume increases
Across-hospital degree × physician volume	4.17e-06 (2.12e-06)	0.05	Across-hospital degree effect increases as volume increases

Note. The models include all study variables (including the main effects) and the interaction term. The interaction effects capture deviations from their corresponding main effects, and the interpretation of these effects are specified in the last column. The estimates and standard errors are presented using the shorthand for exponential notation (ie, e-2 indicates  $\times 10^{-2}$ ).

N.D., no difference.

fatality increased as physician procedure volume increased (est (SE) =  $4.17 \times 10^{-6}$  ( $2.512 \times 10^{-6}$ ),  $P = 0.05$ ).

## 4 | DISCUSSION

There is a well-established positive association between procedure volume and better outcomes.<sup>1-4</sup> Referrals of patients to specialized physicians are not random; they are likely to reflect physician skill, patient needs, and professional relationships between physicians within and across hospitals. We expect that as physicians gain a reputation for positive outcomes following procedures, referral patterns may evolve to channel more complex patients to physicians who achieve better results. The research evaluating physician characteristics other than procedure volume in relation to mortality is limited, but associations between physician clinical experience and specialty and patient outcomes have been shown.<sup>25</sup> Further, a recent study reported decreased acute myocardial infarction mortality during dates of national cardiology meetings, which the authors hypothesized was due to differences in medical management.<sup>26</sup> A deeper understanding of physician and hospital characteristics beyond procedure volume that are associated with better patient outcomes will inform how patients undergoing select surgical procedures should be channeled to specific physicians and hospitals to optimize outcomes.

In this paper, we have distinguished between physician's within-hospital degree centrality and across-hospital degree centrality within a cardiovascular disease patient-sharing network and assessed their relationships with procedure volume and patient outcomes. We observed moderate positive associations between within-hospital and across-hospital degree centrality and procedure volume, suggesting that network centrality is not related solely to volume, but is rather likely a composite of many variables, such as physician clinical and academic expertise, support and recognition among colleagues, hospital reputation, resources, market share, and patient preference.

Our results highlight characteristics of physicians and hospitals that are differentially associated with within-hospital and across-hospital degree centrality, including having a publishing record, practicing at a teaching hospital, and greater market concentration.

But patient-sharing patterns are also likely affected by characteristics of the market, for example, whether the hospital system comprises multiple facilities (making it more likely that the physician would experience greater across-hospital centrality), or whether the physician practices in an environment with narrow networks limiting referrals (making across-hospital centrality less likely). Future work that distinguishes among these various factors would provide insight into the mechanisms for how centrality is associated with lower (or higher) mortality.

Overall, we found that adverse outcomes following ICD therapy were more strongly predicted by physician characteristics rather than hospital characteristics. Our results provide additional evidence to support the inverse association between physician ICD procedure volume and adverse outcomes previously reported.<sup>12-14</sup> Furthermore, within-hospital and across-hospital degree were found to have opposing effects on risk-adjusted 2-year case fatality. These results demonstrate that important clinically relevant information was gained by considering these two degree centrality measures separately.

The negative association between implanting physician local degree and adverse outcomes indicates that patients benefit when treated by physicians who are central within the hospital patient-sharing network. As such, physician's within-hospital degree could be interpreted as a marker for high quality given a fixed volume and in turn provides evidence that selective referral to physicians who are not only high volume but also central within the hospital patient-sharing network leads to better patient outcomes. The Heart Rhythm Society defines an experienced pacemaker implanter as one who implants at least 35 annually.<sup>27</sup> By examining established patient-sharing pathways, health care systems may be better able to use selective referrals to increase adherence to minimum volume guidelines for competency maintenance of ICD therapy recommendations.<sup>27,28</sup>

The increased likelihood for 2-year case fatality among patients treated by physicians with a high across-hospital degree raises several questions. We first hypothesized that we may be observing a form of selection bias; sicker patients are being referred to these high across-hospital degree physicians. If this were the case, the implanting physician's across-hospital degree may capture some unobserved patient selection bias. However, the estimated predicted



case fatality among ICD patients in this study was not associated with across-hospital degree; that is, if the observable factors do not predict across-hospital degree, it seems unlikely that unobserved factors would.

Specialization in a given procedure (ie, the relative extent to which a physician focuses on a specific procedure, independent of absolute clinical volume) was shown to predict lower mortality for several common cardiovascular procedures.<sup>29</sup> Thus, an alternative interpretation of the positive association between across-hospital degree and 2-year case fatality may be that physicians with greater across-hospital degree treat a broader spectrum of cardiovascular disease patients and are potentially less specialized in ICD therapy. Although procedural specialization was not specifically measured in this study, evaluation of the relationship between specialization and across-hospital degree is warranted as they represent important yet distinct aspects of physician reputation and expertise.

Our study is not without limitations. First, we identified relationships between physicians based on the sharing of patients observed using administrative data. Although patient-sharing relationships have been validated,<sup>6</sup> degree centrality does not fully account for other possible confounding factors (eg, reputation, selective referrals, and patient preference) which can influence patient outcomes yet are difficult to measure with administrative data. Second, we built the network based on the sharing of Medicare beneficiaries with a diagnosis of cardiovascular disease. The degree centrality of the physician is therefore interpreted as the connectedness of the physician with other physicians caring for elderly patients with cardiovascular disease and may not be generalizable to cardiovascular patient cohorts less than 65 years of age. Third, this study analyzed an undirected network, meaning we were not able to distinguish whether patients are typically referred from one physician to another. Whether a physician is frequently referred patients would be gleaned from considering a directed network based on temporality of clinical encounters between patients and physicians, which is an important future direction. Third, the procedure volume across physicians is relatively low, with little variation. Future research that considers surgical procedures with greater variation in volume could show stronger associations for within-hospital and across-hospital degree, and health outcomes.<sup>4</sup> Finally, due to the observational study design, our results cannot be interpreted as causal.

In conclusion, within-hospital and across-hospital degree centrality are novel descriptors of physicians that we observe to be related to patient risk-adjusted adverse outcomes following ICD therapy. This study demonstrates how considering physician's within-hospital and across-hospital degree in analyses of procedure volume and mortality allows for more nuanced evaluation of the volume to outcomes relationships. For instance, future works investigating surgical variation may consider surgeon within-hospital degree as a measure of centrality within a patient-sharing network to better predict differences in patient outcomes across surgeons with similar volume. Our approach is broadly applicable, as it is feasible to calculate within-hospital and across-hospital degree centrality for

physicians across a range of disease-specific patient cohorts and at different health system levels given the availability of administrative data.

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## REFERENCES

1. Birkmeyer JD, Dimick JB, Staiger DO. Operative mortality and procedure volume as predictors of subsequent hospital performance. *Ann Surg.* 2006;243(3):411-417.
2. Birkmeyer JD, Siewers AE, Finlayson EVA, et al. Hospital volume and surgical mortality in the United States. *N Engl J Med.* 2002;346(15):1128-1137.
3. Finlayson EVA, Goodney PP, Birkmeyer JD. Hospital volume and operative mortality in cancer surgery: a national study. *Arch Surg.* 2003;138(7):721-725.
4. Birkmeyer JD, Stukel TA, Siewers AE, Goodney PP, Wennberg DE, Lucas FL. Surgeon volume and operative mortality in the United States. *N Engl J Med.* 2003;349(22):2117-2127.
5. Finks JF, Osborne NH, Birkmeyer JD. Trends in hospital volume and operative mortality for high-risk surgery. *N Engl J Med.* 2011;364(22):2128-2137.
6. Barnett ML, Landon BE, O'Malley AJ, Keating NL, Christakis NA. Mapping physician networks with self-reported and administrative data. *Health Serv Res.* 2011;46(5):1592-1609.
7. Barnett ML, Christakis NA, O'Malley AJ, Onnela J-P, Keating NL, Landon BE. Physician patient-sharing networks and the cost and intensity of care in US hospitals. *Med Care.* 2012;50:1-9.
8. Landon BE, Keating NL, Barnett ML, et al. Variation in patient-sharing networks of physicians across the United States. *JAMA.* 2012;308(3):265-273.
9. Funk RJ, Owen-Smith J, Kaufman SA, Nallamothu BK, Hollingsworth JM. Association of informal clinical integration of physicians with cardiac surgery payments. *JAMA Surg.* 2018;153(5):446-453.
10. Landon BE, Keating NL, Onnela J-P, Zaslavsky AM, Christakis NA, O'Malley AJ. Patient-Sharing networks of physicians and health care utilization and spending among Medicare beneficiaries. *JAMA Intern Med.* 2018;178(1):66-73.
11. Milstein A, Galvin RS, Delbanco SF, Salber P, Buck CR. Improving the safety of health care: the leapfrog initiative. *Eff Clin Pract.* 2000;3(6):313-316.
12. Al-Khatib SM, Lucas FL, Jollis JG, Malenka DJ, Wennberg DE. The relation between patients' outcomes and the volume of cardioverter-defibrillator implantation procedures performed by physicians treating Medicare beneficiaries. *J Am Coll Cardiol.* 2005;46(8):1536-1540.
13. Freeman JV, Wang Y, Curtis JP, Heidenreich PA, Hlatky MA. Physician procedure volume and complications of cardioverter-defibrillator implantation. *Circulation.* 2012;125(1):57-64.

14. Freeman JV, Wang Y, Curtis JP, Heidenreich PA, Hlatky MA. The relation between hospital procedure volume and complications of cardioverter-defibrillator implantation from the implantable cardioverter-defibrillator registry. *J Am Coll Cardiol*. 2010;56(14):1133-1139.
15. Moen EL, Bynum JP, Austin AM, Skinner JS, Chakraborti G, O'Malley AJ. Assessing variation in implantable cardioverter defibrillator therapy guideline adherence with physician and hospital patient-sharing networks. *Med Care*. 2018;56(4):350-357.
16. Jena AB, Khullar D, Ho O, Olenski AR, Blumenthal DM. Sex differences in academic rank in US medical schools in 2014. *JAMA*. 2015;314(11):1149.
17. Jena AB, Olenski AR, Blumenthal DM. Sex Differences in physician salary in US public medical schools. *JAMA Intern Med*. 2016;176(9):1294.
18. Bynum JPW, Bernal-Delgado E, Gottlieb D, Fisher E. Assigning ambulatory patients and their physicians to hospitals: a method for obtaining population-based provider performance measurements. *Health Serv Res*. 2007;42(1p1):45-62.
19. An C, O'Malley AJ, Rockmore DN, Stock CD. Analysis of the U.S. patient referral network. *Stat Med*. 2018;37(5):847-866.
20. Moen EL, Austin AM, Bynum JP, Skinner JS, O'Malley AJ. An analysis of patient-sharing physician networks and implantable cardioverter defibrillator therapy. *Health Serv Outcomes Res Method*. 2016;16(3):132-153.
21. Csárdi G, Nepusz T. The igraph software package for complex network research. *Interjournal*. Complex Systems, 1695.
22. R Development Core Team. R: A language and environment for statistical computing. <http://www.R-project.org>.
23. Colla C, Bynum J, Austin A, Skinner J. *Hospital Competition, Quality, and Expenditures in the US Medicare Population*. Cambridge, MA: National Bureau of Economic Research; 2016.
24. Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *J Stat Softw*. 2015;67(1):1-48.
25. Schmidt CM. Effect of hospital volume, surgeon experience, and surgeon volume on patient outcomes after pancreaticoduodenectomy. *Arch Surg*. 2010;145(7):634-640.
26. Jena AB, Olenski A, Blumenthal DM, Yeh RW, Goldman DP, Romley J. Acute myocardial infarction mortality during dates of national interventional cardiology meetings. *J Am Heart Assoc*. 2018;7(6):e008230.
27. Alkaabi S, Elhag O, Sabbour H, Alsheikh-Ali A. Requirements for achieving and maintaining competency in the implantation and management of cardiac implantable electrical devices: a clinical competency statement by the Emirates Cardiac Society. *Heart Views*. 2013;14(3):97-100.
28. Hayes DL, Naccarelli GV, Furman S, et al. NASPE Training requirements for cardiac implantable electronic devices: selection, implantation, and follow-up. *Pacing Clin Electrophysiol*. 2003;26(7p1):1556-1562.
29. Sahni NR, Dalton M, Cutler DM, Birkmeyer JD, Chandra A. Surgeon specialization and operative mortality in United States: retrospective analysis. *BMJ*. 2016;354:i3571.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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