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Physician network position and patient outcomes following implantable cardioverter defibrillator therapy

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Abstract

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 2007-11.

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 within-hospital and across-hospital degree centrality on case fatality. We included 105,109 ICD therapy patients and 3,474 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 ($\text{OR (95\% CI)} = 1.10\ (1.04 - 1.16)$ $, p = 0.001$) and lowest tertile volume physicians compared with highest volume ($\text{OR (95\% CI)}$ $= 0.90\ (0.84 - 0.95), p < 0.001$). Physician 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.

Key Words. physician network, degree centrality, implantable cardioverter defibrillator, case fatality

INTRODUCTION

An inverse association between patient mortality and surgeon and hospital procedure volume is one of the strongest empirical regularities in health services research.[1-4] 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,[5] 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.[6] 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,[7-10] 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.[11]

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,[12-14] 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,[15] 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 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.

METHOD

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 2007-11. 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 Parts 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 in-patient 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 healthcare professionals in the US, with over 70% of US physicians as verified members and was used to obtain additional physician characteristics. Doximity data has been used and verified in previous studies.[16,17] 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 calculated socioeconomic indicators. The institutional review board of Geisel School of Medicine at Dartmouth approved the study protocol.

Attribution of physicians to hospitals

Physicians were empirically attributed to hospitals using the physician hospital network methodology developed previously.[18] The attribution was based on the hospital where s/he 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 were admitted.

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[19] or bounded using previously developed algorithms to assign physicians to "groups" (e.g., hospitals or hospital referral regions).[15,20] 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 sub-network and on the complement of the sub-network. 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 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[21] in R.[22]

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, non-ischemic 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,[15] 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 (i.e., 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) to all 2010 AHA hospitals (destinations) within an 8-hour (480 minute) cut-off 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.

ICD 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.[23] 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.[15]

Assessment of outcome

The primary outcome variable of interest was the binary indicator of whether or not the patient died within the two 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.

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 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 or not 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 (e.g., 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:

$$\Pr\left(y_{ijkl} = 1 \,\middle|\, \theta_j, \delta_k, \gamma_l, Year_{ijkl} = t + 1\right) = \text{logit}^{-1}(\beta_0 + \beta_1 Pat_{ijkl} + \beta_2 Phys_{jklt} + \beta_3 Hosp_{klt} + \theta_j + \delta_k + \gamma_l)$$

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

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 $Year_{ijkl}$), the predictors particular to a given physician are depicted by *Phys*, the descriptors of the hospital are depicted by *Hosp*. Random effects for physician, hospital, and HRR are depicted as θ_j , δ_k, and γ_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[24] in the R statistical software.

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 3,474 implanting physicians (primarily electrophysiologist cardiologists and thoracic surgeons) within 1,280 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 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 within-hospital degree was positively associated with ICD procedure volume (*rho* = 0.23) and hospital ICD volume (*rho* = 0.30). The implanting physician 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 Appendix Table 1. 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 ($p<0.001$), and practice at a teaching hospital ($p<0.001$), a high degree hospital ($p<0.001$), and to 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 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 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 tertile ($\mathrm{OR} = 0.96\ (0.91 - 1.01), p > 0.05$). 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 ($\mathrm{OR} = 1.10\ (1.04 - 1.16), p < 0.001$).

To explore associations between physician 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 within-hospital and across-hospital degree with short-term adverse events remained (negative and positive, respectively), although they were no longer statistically significant (Appendix Table 2). Physician ICD procedure volume was also significantly negatively associated with short-term adverse events (p=0.02) (Appendix Table 2).

Next, we evaluated whether the ICD procedure volume-outcomes relationships were affected by the inclusion of implanting physician 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, $\mathrm{OR} = 0.90\ (0.84 - 0.95), p < 0.001$) (Appendix Table 3); hospital volume was not statistically significant (top tertile compared to bottom tertile, $\mathrm{OR} = 0.97\ (0.91 - 1.03), p > 0.05$). When within-hospital and across-hospital physician degree were excluded, the effect of physician procedure volume on case fatality was slightly attenuated ($\mathrm{OR} = 0.92\ (0.87 - 0.97, p = 0.004)$, and the effect of hospital procedure volume on case fatality was unchanged ($\text{OR} = 0.95\ (0.89 - 1.01, p > 0.05)$ (Appendix Table 3).

To further characterize how implanting physician degree and volume are related to patient outcomes, we tested for significant interactions between physician 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 ($est\ (std\ err) = 1.49\ \times 10^{-5}\ (7.13\ \times 10^{-6})$ $, p = 0.04$); 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 fatality increased as physician procedure volume increased (est $(std\ err) = 4.17 \times 10^{-6}\ (2.512\ \times 10^{-6}), p = 0.05$).

DISCUSSION

There is a well-established positive association between procedure volume and better outcomes.[1-4] Yet 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.[25] 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.[26] 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 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 was 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.[12-14] 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 within-hospital degree could be interpreted as a marker for high quality given a fixed volume, and in turn provide 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. [27] 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.[27,28]

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 (i.e., 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.[29] 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,[6] degree centrality does not fully account for other possible confounding factors (e.g., 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.[4] 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 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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Table 1: Characteristics of patients, ICD implanting physicians, and hospitals according to

	Within-hospital degree				*Across-hospital degree*			
Characteristics	*Low (1-74)*	*Medium (75-114)*	*High (115-448)*	*p-value*$^{\psi}$	*Low (1-186)*	*Medium (187-308)*	*High (308-1,055)*	*p-value*$^{\psi}$
ICD patients, n	25,488	34,414	42,189	<0.001	23,816	35,263	45,989	<0.001
Age in years, median (1st, 3rd q)	73 (67, 79)	73 (67, 79)	73 (67, 79)	n.s.	73 (67, 79)	73 (67, 79)	73 (67, 79)	n.s.
Male, %	72	72	72	n.s.	73	73	72	n.s.
Race								
White, %	83	86	84	<0.001	86	86	82	<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)	0.05	32 (49)	32 (45)	32 (46)	n.s.
ICD physician (n=3,474)								
ICD procedure volume per year, mean (sd)	15 (n.r.)	19 (n.r.)	24 (n.r.)	<0.001	19 (n.r.)	27 (15)	37 (21)	<0.001
Specialty: cardiology, %	77	89	94	<0.001	74	92	98	<0.001
Publishing record, %	53	56	59	0.001	58	55	54	0.02
Participates in clinical trials, %	15	20	22	<0.001	19	17	22	<0.001
ICD hospital (n=1,280)								
Hospital volume per year, mean (sd)	49 (n.r.)	59 (n.r.)	87 (64)	<0.001	59 (n.r.)	61 (n.r.)	70 (n.r.)	<0.001
Teaching hospital, %	16	20	33	<0.001	27	21	21	<0.001
Hospital degree, mean (sd)	484 (278)	570 (313)	734 (374)	<0.001	546 (332)	563 (299)	687 (370)	<0.001

physician within-hospital and across-hospital degree

Hospital HHI, mean	0.17	0.19	0.22		0.25	0.21	0.15	
(sd)	(0.14)	(0.15)	(0.15)	<0.001	(0.18)	(0.14)	(0.12)	<0.001

Note The range for each degree tertile is included in parentheses underneath the column headers. sd, standard deviation; q, quartile; n.s., non-significant (*p*-value > 0.05). n.r. indicates that the standard deviation for procedure volume was not reported due to CMS data suppression policies. [Ψ] *p*-values were calculate using two-way ANOVA tests and Pearson Chi-squared tests.

Table 2: Estimated effects on risk-adjusted 2-year case fatality following ICD therapy.

Characteristic	*Estimate (std err)*	*p-value*
Physician variables		
Within-hospital degree	-4.94e-4 (2.35-4)	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
Hospital variables		
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
Patient risk-adjustment variables		
Age	2.78e-2 (9.35e-4)	< 0.001
Female	-9.79e-2 (1.90e-2)	<0.001
Race		
White	-6.58e-2 (2.41e-1)	0.78
Black	1.33e-1 (2.42e-1)	0.58
Median income of zipcode	-1.51e-6 (7.94e-7)	0.06
% living below poverty line of zipcode	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
Ventricular tachycardia		
No	referent	referent
Yes, non-sustained	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
NYHA symptom class		
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
Duration of symptoms since heart failure onset		
< 3 months	referent	referent
3 – 9 months	-1.64e-1 (3.31e-2)	<0.001
> 9 months	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
Previous ICD		
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
NIDCM		
No	referent	referent
Yes, within past 3 months	-2.24e-1 (3.43e-2)	<0.001
Yes, 3-9 months	-3.27e-1 (6.58e-2)	<0.001
Yes, greater than 9 months	-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 days of ICD implant	1.01e-1 (2.60e-2)	<0.001
Yes, greater than 40 days	-8.04e-3 (2.48e-2)	0.75
Yes, both within 40 days and greater than 40 days	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 months	-1.13e-1 (2.51e-2)	<0.001
Yes, greater than 3 months	-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 (i.e., e-2 indicates $\times 10^{-2}$). HHI, Herfindahl-Hirschman Index; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction; CABG, coronary artery bypass grafting; PCI percutaneous coronary intervention; NIDCM, non-ischemic dilated cardiomyopathy; MI, myocardial infarction.

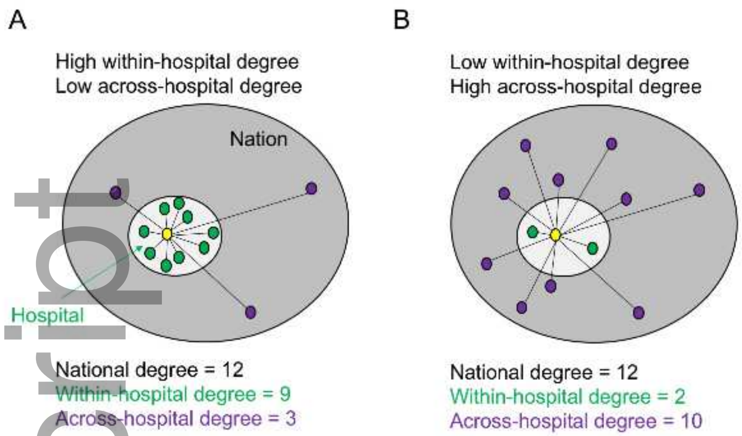
Table 3: Estimation of interaction effects between implanting physician within-hospital and across-hospital degree and procedure volume on predicting 2-year case fatality with multivariable logistic regression.

Interaction model	*Estimate (std err)*	*p-value*	*Interpretation*
Within-hospital degree x physician volume	1.49e-05 (7.13e-06)	0.04	Within-hospital degree effect decreases as volume increases
Across-hospital degree x 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 (i.e., e-2 indicates $\times 10^{-2}$). N.D., no difference).

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.



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