The Effects of Market Competition on Cardiologists' Adoption of Transcatheter Aortic Valve Replacement

Peter W. Groeneveld, MD, MS,*†‡§ Lin Yang, MS,*† Andrea G. Segal, MS, MPH,*†§ Pinar Karaca-Mandic, PhD,||¶ and Genevieve P. Kanter, PhD*†‡#

Background: For decades, the prevailing assumption regarding the diffusion of high-cost medical technologies has been that competitive markets favor more aggressive adoption of new treatments by health care providers (ie, the "Medical Arms Race"). However, novel regulations governing the adoption of transcatheter aortic valve replacement (TAVR) may have disrupted this paradigm when TAVR was introduced.

Objective: The objective of this study was to assess the relationship between the market concentration of physician group practices and the adoption of TAVR in its first years of use.

Research Design: This was a retrospective cohort study.

Subjects: Physician group practices (n = 5116) providing interventional cardiology services in the United States from May 1, 2012, to December 31, 2014.

Measures: The first use of TAVR as indicated by a fee-for-service Medicare claim. Covariates including characteristics of the physician groups (ie, case volume, hospital affiliation, mean patient risk) as well as county-level and market-level characteristics.

Results: By the close of 2014, 9.3% of practices had adopted TAVR. Cox proportional hazards models revealed a hazard ratio of 1.26 (95% confidence interval: 1.16–1.37, $P < 0.001$) per 1000 point increase in the physician group practice Herfindahl-Hirschman Index, indicating each 1000 point increase in group practice Herfindahl-Hirschman Index was associated with a 26% relative increase in the rate of TAVR adoption.

Conclusions: Adoption of TAVR by physician groups in concentrated markets was potentially a consequence of the unique regulations governing TAVR reimbursement, which favored the adoption of TAVR by physician groups with greater market power. These findings have important implications for how future regulations may shape patterns of technology adoption.

Key Words: cardiology, health care markets, integrated health care, market competition, physician practice patterns, technology

(*Med Care* 2020;00: 000–000)

From the *Division of General Internal Medicine, Perelman School of Medicine, University of Pennsylvania; †Cardiovascular Outcomes, Quality, and Evaluation Research Center, University of Pennsylvania School of Medicine; ‡Leonard Davis Institute of Health Economics; §Corporal Michael J. Crescenz Veterans Affairs Medical Center, Philadelphia, PA; ||University of Minnesota Carlson School of Management, Minneapolis, MN; ¶National Bureau of Economic Research; and #Department of Medical Ethics and Health Policy, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA.
Supported by Agency for Healthcare Research and Quality Grant #1R01-HS023615.
P.K.-M. provided consulting services to Tactile Medical and Precision Health Economics for projects unrelated to this work. The remaining authors declare no conflict of interest.
Correspondence to: Peter W. Groeneveld, MD, MS, 1204 Blockley Hall, 423 Guardian Drive, Philadelphia, PA 19104. E-mail: petergro@upenn.edu.
Supplemental Digital Content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's website, www.lww-medicalcare.com.

ISSN: 0025-7079/20/000-000

Transcatheter aortic valve replacement (TAVR) was introduced into clinical practice in 2011–2012 as an alternative therapy to standard aortic valve replacement for patients with aortic stenosis deemed at high risk for perioperative complications.[1] The 2011 Food and Drug Administration's (FDA) initial approval of TAVR,[2] and subsequent 2012 Centers for Medicare and Medicaid Services (CMS) National Coverage Determination,[3] presented an opportunity for interventional cardiology physician groups to expand their repertoire of clinical services to include this high-profile and potentially lucrative new procedure. Medicare reimbursed physicians for TAVR at a relatively high relative-value-unit-based fee compared with other interventional cardiology physician services,[4] and since TAVR was a potential substitute for cardiac surgery it represented an opportunity for cardiologists to expand practice into a clinical domain previously occupied exclusively by cardiac surgeons. However, CMS also established an extensive set of clinical, structural (eg, on-site cardiac surgery) experiential (eg, sufficient prior case volume of similar procedures), and administrative (eg, registry participation) requirements for physicians and hospitals to qualify for TAVR reimbursement,[3] hence there were also substantial barriers to physician groups interested in providing TAVR.

Prior evaluations of medical technology adoption have generally found that in fee-for-service environments, health care markets with higher levels of competition among hospitals had more rapid adoption than less competitive markets,[5–10] in what has colloquially been described as the "Medical Arms Race."[11] While this phenomenon generally has been associated with overuse of medical technology (ie, use of technology that provides no benefit),[12] in the case of TAVR the adoption of the

procedure by an excessive number of interventional cardiology groups in competitive markets could have important adverse quality consequences because the total number of eligible patients in any market is limited, and lower case volumes often result in suboptimal patient outcomes from complex cardiovascular procedures.[13,14]

The purpose of our study was to examine TAVR adoption among interventional cardiology practices during its first years of nonexperimental use (ie, 2012–2014) to determine if the market competition was a significant adoption driver.

METHODS

Cohort Selection

To identify physician groups that were candidates for TAVR adoption in 2012–2014, we first selected a cohort of physicians who had Medicare Part B (ie, provider) claims with Current Procedural Terminology (CPT) codes indicating the physician had performed interventional cardiology procedures (coronary angiography, percutaneous coronary intervention, and/or catheter-delivered structural heart disease repair) among fee-for-service Medicare beneficiaries in 2011 (Appendix 1, Supplemental Digital Content 1, http://links.lww.com/MLR/C93). Because of occasional CPT coding errors on these claims, we required a minimum of 5 paid fee-for-service Medicare claims for interventional cardiovascular services in 2011 to classify a physician as an interventional cardiologist. We restricted the cohort to physicians in the contiguous 48 states or the District of Columbia as indicated by the location of the plurality of their Medicare Part B claims. We further restricted the cohort to physicians who remained in practice during 2012–2014 as evidenced by their submitting at least 5 Part B claims to Medicare during these 3 years. While noncardiologists (ie, surgeons) also provide TAVR, Medicare requires the participation of an interventional cardiologist at each TAVR procedure,[3] thus we focused this analysis solely on physician groups with interventional cardiologists.

Identification of Physician Group Practices, and Group Practice Characteristics.

For each physician identified using the methods described above, the most common Federal Tax Identification Number (TIN) reported on his/her Part B claims during 2012–2014 was used to identify the physician's group practice. The Federal TIN indicates the billing entity that will receive payment for the medical service; the range of physicians represented by a particular TIN can range from 1 (for a physician in solo practice) to potentially over 1000 in large, multispecialty integrated health systems.

Group Practice Characteristics

For each group practice identified following the methods described above, we used 2011 Medicare Part B claims to determine if the group had prior experience providing structural heart repair (eg, repair of patent foramen ovale, etc.) since CMS required experience in providing such procedures for physicians seeking to provide TAVR.[3] The group's interventional cardiology case volume was estimated by counting the number of unique Medicare beneficiaries with an interventional cardiology procedural claim from all physicians affiliated with the practice. The mean comorbidity of the group's Medicare patient population was estimated by calculating a mean CMS Hierarchical Condition Category risk score for all patients in 2011 with a billed clinical encounter with interventional cardiologists affiliated with the group,[15] including both patients who had undergone interventional procedures as well as those who did not.

Hospital Identification and Characteristics

Because physician groups may have been strongly influenced by their affiliated hospitals, each group's primary affiliated hospital was identified by using the Medicare Part A claim linked by patient identifier and date to a physician group's Part B claim for an interventional cardiology procedure, to determine the hospital where the plurality of each physician group's interventional cardiology procedures were performed among fee-for-service Medicare beneficiaries in 2011. Membership in the Council of Teaching Hospitals and Health Systems in 2012 as indicated by the American Hospital Association's annual survey was used as an indicator of which hospitals were academic centers. Published lists of the participating hospitals in the 2 large randomized controlled trials of TAVR that served as the basis for the first FDA approvals of the device (ie, the Placement of AoRTic TraNscathetER Valve Trial and the US CoreValve High Risk Study) were used to identify hospitals where TAVR had been used experimentally before FDA approval.[16,17]

Identification of Health Care Markets

Consistent with multiple prior studies of health care markets, we used the Dartmouth Atlas for Health Care's Hospital Referral Regions (HRRs) as the definition of markets for TAVR.[18] These are contiguous geographic areas ($n = 306$) in which the vast majority of Medicare beneficiaries obtain their health care (ie, travel across HRR boundaries to obtain health care is uncommon), and which have at least one hospital that performs major cardiovascular procedures and neurosurgery, with a minimum population of 120,000. Physician groups were assigned to HRRs based on the physician group's billing ZIP code. Any physician group with billing ZIP codes located in >1 HRR was treated as unrelated, independent practices within each of those HRRs.

Measurement of Physician Group Practice Concentration

The classic measure of market concentration is the Herfindahl-Hirschman Index (HHI), which is mathematically derived from the observed market share of all competitors in a given market.[19] This method results in an endogenous measure of market concentration because observed market share is a function of unobservable factors (eg, local reputation, affiliation with a university hospital, perceived quality, etc.) that potentially bias the HHI away from a pure measure of market competition.[7] Several prior investigations have addressed this issue by constructing an "exogenous" HHI based solely on the geographic availability of health care providers

(ie, group practices or hospitals) to patients living in ZIP codes within a fixed radius (typically 50 miles) of the provider's ZIP code.[7,8,20] We used similar methods (Appendix 2, Supplemental Digital Content 2, http://links.lww.com/MLR/C94) to construct exogenous HHIs for the current study for both hospitals and for physician groups practices, and these exogenously-constructed HHIs—referred henceforth as HHI_{exog}—were used as the primary measures of market competition in our analyses. Our HHI_{exog} measure was independent of HRR geographic boundaries and solely reflected the choice set of cardiology practices for patients living within 50 miles of each practice.

Medicare Managed Care

Over 25% of Medicare beneficiaries were covered by Medicare managed care during 2012–2013.[21] We hypothesized that markets with high penetration rates of Medicare managed care may have different rates of TAVR adoption than markets with lower penetration rates, because of the incentives to reduce costs in managed care patients. Hence, we used Medicare's Master Beneficiary Summary Files to calculate county-level measures of Medicare managed care penetration in 2011 to include in our fully specified models, as well as county-level measures of change in Medicare Advantage enrollment between 2011 and 2014.

County-level Variables

County-level socioeconomic and health care control variables included per capita income, percentage of the population over age 65, and educational attainment measures from the 2010 US Census, the county's rural/urban classification (US Department of Agriculture), hospital beds per capita, and the presence of a hospital with a coronary care unit as reported in the 2011 American Hospital Association Survey, and physicians per capita (a general measure of health care supply) as reported in the 2010 American Medical Association Physician Masterfile.

Transcatheter Aortic Valve Replacement Adoption

Because most TAVR recipients are older than age 65,[1] the vast majority of TAVR recipients are Medicare beneficiaries, and thus Medicare claims are a comprehensive source of data to measure TAVR adoption. The adoption of TAVR by a physician group practice was indicated by the appearance of a Part B claim for TAVR (CPT codes 0256T, 0257T, or 33361–33366) by at least 1 physician in the practice after the CMS coverage approval date of May 1, 2012.

Statistical Analyses

We modeled adoption as a Cox proportional hazards time-to-event model, with the dependent variable being the days elapsed between May 1, 2012, and the date of first use of TAVR by a group practice. Practices that had not adopted TAVR at any point during the 32-month observation period (ie, May 2012 through December 2014) were censored on December 31, 2014. Independent variables in the model included market-level variables (physician group practice HHI_{exog}, hospital HHI_{exog}, and the market's population size), group practice characteristics (mean CMS Hierarchical Condition Category risk score, interventional case volume, academic hospital affiliation, and TAVR clinical trial hospital affiliation). The full model (detailed specification in Appendix 3, Supplemental Digital Content 3, http://links.lww.com/MLR/C95) also included the county-level control variables described above. All variables were tested to assure that the proportional hazards assumption (ie, time independence) was met, and when a time-dependent variable was identified, interaction with the variable and time was added to the model.

Subgroup Analyses and Robustness Tests

Because of the regulatory requirement that cardiologists performing TAVR have substantial prior structural heart procedural experience (eg, catheter-delivered repair of congenital heart defects),[3] we anticipated that physician groups with prior structural heart disease procedural experience may have adopted TAVR at much different rates than physician groups without this prior experience, so a subgroup analysis based on this characteristic was predefined. In addition, because the effect of market competition may have been influenced by managed care penetration, we tested for interaction effects of physician group HHI_{exog} with hospital HHI_{exog}, physician group HHI_{exog} with Medicare Advantage penetration, and hospital HHI_{exog} with Medicare Advantage penetration. We also conducted robustness checks of our model's specification and functional form.

The University of Pennsylvania's Institutional Review Board approved the research protocol. All analyses were conducted using SAS 9.2 (SAS Institute, Cary, NC) and/or Stata 16.1 (StataCorp, College Station, TX).

RESULTS

We identified 5116 physician group practices that provided interventional cardiology services in 2011 (Table 1). Thirty percent of these practices were solo-physician, 20% were affiliated with a teaching hospital, and 75% performed > 100 interventional cardiology cases per year. Approximately 10% of cardiology groups were affiliated with hospitals that had participated in TAVR clinical trials. There was substantial geographic variation in the market concentration of physician groups providing interventional cardiology services at the time of TAVR's introduction (Fig. 1); the median interventional cardiology group practice HHI_{exog} was 1600 [interquartile range (IQR): 900–2600]. Similarly, there was substantial variation in the market concentration of hospitals; the median hospital HHI_{exog} was 3100 (interquartile range: 1900–4700).

Adoption of Transcatheter Aortic Valve Replacement by Physician Group Practices

Among the 5116 group practices in our study cohort, 475 (9.3%) practices adopted TAVR during 2012–2014. Among the 274 practices with prior structural heart disease procedural experience, 175 (64%) adopted TAVR, however among the 4850 practices without such experience, only 300 (6.2%) adopted TAVR. We observed substantial variation in the proportion of interventional cardiology practices within health care markets (ie, HRRs) that had adopted TAVR during 2012–2014. Across the 304 HRRs in the contiguous

TABLE 1. Interventional Cardiology Group Characteristics

Characteristics	Practices (N = 5116) [n (%)]
No. physicians per physician group practice in 2011	
1	1534 (30)
2–5	1116 (22)
6–20	846 (17)
21–50	477 (9)
51–100	373 (7)
> 100	770 (15)
Annual case volume per physician group practice in 2011*	
1–99	1289 (25)
100–199	1399 (27)
200–399	1637 (32)
400–699	607 (12)
700–999	136 (3)
1000–1999	52 (1)
≥ 2000	4 (0.1)
Annual case volume per interventional cardiologist in 2011	
1–100	1502 (29)
101–200	1526 (29)
201–400	1348 (27)
> 400	740 (15)
US Census region	
Midwest	1047 (20)
South	2063 (40)
Northeast	940 (19)
West	1066 (21)
Urban location†	2867 (56)
Physician group affiliated with academic hospital‡	1038 (20)
Physician group affiliated with a TAVR clinical trial hospital§	505 (10)
Mean HCC risk quartile (range of HCC risk scores)	
Highest (2.97–7.63)	1280 (25)
Second (2.60–2.97)	1279 (25)
Third (2.30–2.60)	1279 (25)
Lowest (0.75–2.30)	1278 (25)
Healthcare Referral Region Medicare beneficiary population in 2011	
≤ 50,000	781 (15)
> 50,000–100,000	1201 (24)
> 100,000–200,000	1513 (30)
> 200,000–400,000	1082 (21)
> 400,000	539 (11)
Percentage of Medicare beneficiaries in each physician group practice's county enrolled in Medicare Advantage	
≤ 10	572 (11)
> 10–20	1322 (26)
> 20–30	1131 (22)
> 30–40	1127 (22)
> 40–50	667 (13)
> 50	297 (6)
Market concentration (HHI_{exog}) in physician group practice's market	
0–1999	3134 (61)
2000–3999	1469 (29)
4000–5999	396 (7.7)
6000–7999	94 (1.8)
8000–10,000	26 (0.5)

*Case volume for interventional cardiology procedures in 2011 among fee-for-service Medicare beneficiaries.

†Urban location is defined as the medical group's county Federal Information Processing Standards code linked with Rural-Urban Continuum Codes.

‡Academic hospitals defined as members of the Council of Teaching Hospitals and Health Systems.

§Physicians affiliated with hospitals that participated in the TAVR Clinical Trial Hospitals before the Food and Drug Administration (FDA) approval of TAVR, that is, the Placement of AoRTic TraNscathetER Valve Trial (PARTNER) and the US CoreValve High Risk Study.

HCC indicates Centers for Medicare and Medicaid Services Hierarchical Condition Category; HHI_{exog}, exogenous Herfindahl-Hirschman Index; TAVR, transcatheter aortic valve replacement.

48 states plus the District of Columbia, the median HRR-level percentage of TAVR adoption was 7.4% (IQR: 0%–15.3%). No TAVR adoption occurred in 111 HRRs, while only 1 physician group practice adopted TAVR in 78 HRRs, and > 1 group practice adopted TAVR in the remaining 115 HRRs.

Unadjusted Association of Market Competition and Transcatheter Aortic Valve Replacement Adoption Rates

Physician group practices in the highest (ie, most concentrated) tertile for HHI_{exog} adopted TAVR at higher rates than practices in the middle or lowest (ie, most competitive) tertiles for HHI_{exog} (log-rank test $\chi^2 = 11.24$, $P = 0.004$) (Fig. 2). By the end of 2014 (974 d after CMS coverage approval), 11.0% of practices in the most concentrated HHI_{exog} tertile had adopted TAVR, compared with 9.1% of practices in the middle HHI_{exog} tertile, and 7.7% of practices in the lowest HHI_{exog} tertile ($P < 0.001$).

Multivariable Results for Market-level Concentration

Tests of correlation among our independent variables revealed no substantial multicollinearity (ie, all variance inflation factors <2.5). The fully specified multivariable model (Table 2) revealed a hazard ratio of 1.26 [95% confidence interval (CI): 1.16–1.37, $P < 0.001$] per 1000 increase in physician group practice HHI_{exog}, indicating each 1000 increase in group practice HHI_{exog} was associated with a 26% higher rate of TAVR adoption. Conversely, the hazard ratio for hospital HHI_{exog} was 0.90 (95% CI: 0.83–0.98, $P = 0.02$), indicating each 1000 increase in hospital HHI_{exog} resulted in a 10% lower rate of TAVR adoption. The inclusion of additional control variables in our models had minimal impact on the magnitude of the measured effect of HHI_{exog} for both physician group practices and hospitals. We also observed a hazard ratio of 1.25 (95% CI: 1.15–1.37, $P < 0.001$) for managed care penetration, indicating each 10 percentage point increase in (county-level) managed care penetration was associated with a 25% relative increase in the rate of TAVR adoption.

Subgroup Analysis

Because prior experience with structural heart repair by the interventional cardiologist performing TAVR was a requirement in the CMS National Coverage Determination for TAVR, we expected that TAVR adoption rates would differ markedly between physician group practices with prior structural heart repair experience versus those practices that lacked prior structural heart experience (the latter practices would presumably have had to recruit an interventional cardiologist with the necessary procedural experience to offer TAVR services). We, therefore, analyzed TAVR adoption of these 2 subgroups (Appendix 4, Supplemental Digital Content 4, http://links.lww.com/MLR/C96). The subgroup results showed a very similar pattern of increased adoption of TAVR in markets with greater physician group concentration, with the hazard ratio for TAVR adoption per 1000 increase in $HRR_{exog} = 1.19$ ($P = 0.07$) in the 266 physician groups with

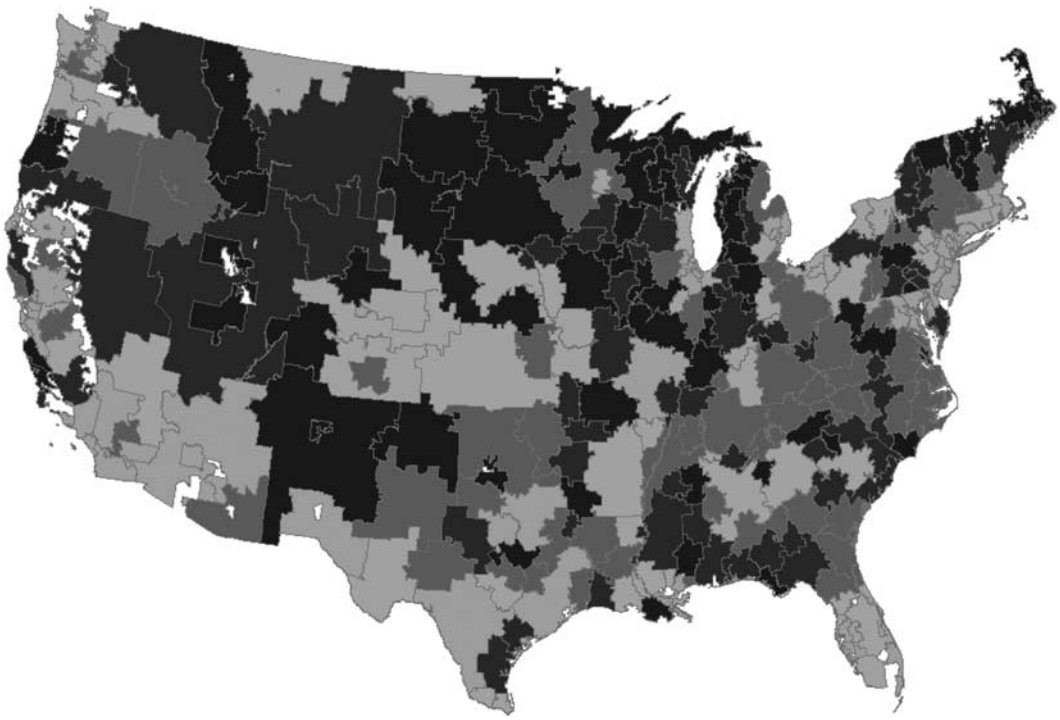

FIGURE 1. Market concentration of interventional cardiology physician group practices among US health care markets. Health care markets, defined as the 304 HRRs in the 48 contiguous United States and the District of Columbia, are shaded by quintile of mean HHI_{exog} in each HRR for physician group practices that offered interventional cardiology services. Light gray indicates the lowest HHI_{exog} level (ie, the most competitive markets; $HHI_{exog} = 500–2200$), while increasingly darker shades of gray indicate greater market concentration (ie, less competitive markets). Gray indicates $HHI_{exog} = 2200–3100$, dark gray indicates $HHI_{exog} = 3100–4000$, and black indicates $HHI_{exog} = 4000–10{,}000$. HHI_{exog} indicates exogenous Herfindahl-Hirschman Index; HRR, Hospital Referral Region.

prior structural heart repair experience, and 1.21 ($P = 0.001$) in the 4632 physician groups without prior structural heart repair experience.

Robustness

Variation in functional form and model specification, as well as subgroup testing, produced no material differences in the direction or statistical significance of the relationship between HHI_{exog} and TAVR adoption (Appendix 3, Supplemental Digital Content 3, http://links.lww.com/MLR/C95).

DISCUSSION

Adoption of TAVR was more common in 2012–2014 by physician groups located in health care markets that were less competitive, a result that was consistent across subgroups and robust to the choices of functional form and specification of our analytic models. This finding is contrary to the "Medical Arms Race" paradigm that has been the leading theoretical construct explaining the relationship between market concentration and technology adoption. A secondary finding is that TAVR adoption was more common by physician groups located in markets with higher managed care penetration, a finding also at odds with previous work suggesting managed care slows the adoption of high-technology medical services.

Why Transcatheter Aortic Valve Replacement Was Adopted by Physician Groups in Less Competitive Markets

There are unique aspects to TAVR and the national coverage determination regulations governing its use that may explain its more frequent adoption in more monopolistic markets. First, CMS required TAVR to be performed by interventional cardiologists with at least 100 prior structural heart procedures. It is possible that physician group practices having a dominant share of interventional procedures in their market were more likely to have members of the group who met these stringent qualifications. Conversely, group practices in competitive markets with smaller market shares may have struggled to meet the procedural volume requirements. Second, it is possible that within any given market there was a particular benefit to being among the first physician groups to offer TAVR because the establishment of a successful TAVR program requires an ample supply of qualified patients, and these patients may have been harder to attract in markets that already had active TAVR providers. The opportunity to become the first TAVR-providing entrant in a market was more common in markets with fewer competitors. A third possibility is that TAVR services required investment on the part of physician group practices in the acquisition of new skills by designated members of the practice, and/or by recruitment

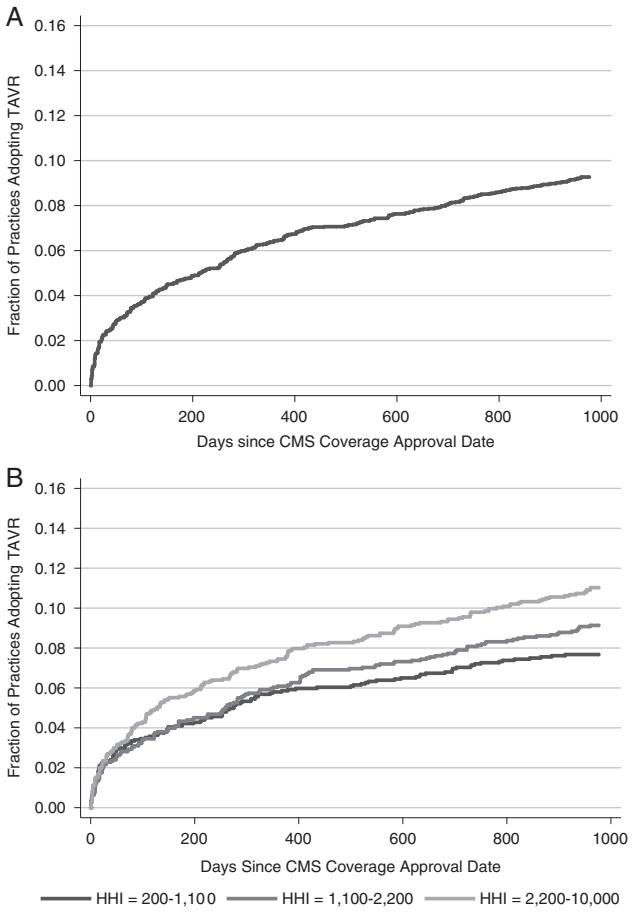

FIGURE 2. Unadjusted adoption of TAVR from 2012 to 2014 by Physician Group Practices offering Interventional Cardiology Services, overall and by tertile. A, The fraction of all physician group practices, as indicated on the *y*-axis, that offered interventional cardiology services that had submitted at least 1 Part B claim to Medicare for TAVR by the date indicated on the *x*-axis. B, The adoption rate among 3 equal-sized subgroups of practices located in health care markets with high concentration (light gray), moderate concentration (gray), and low concentration (dark gray) of physician group practices, as defined by tertiles of HHI_{exog}. CMS indicates Centers for Medicare and Medicaid Services; HHI_{exog}, exogenous Herfindahl-Hirschman Index; HHI, Herfindahl-Hirschman Index; TAVR, transcatheter aortic valve replacement.

of physicians with these skills to the practice. It is possible that the resources needed for this upfront investment in additional training/recruitment and knowledge/skills acquisition were primarily available at group practices in concentrated markets, where practice profits would be expected to be higher than in more competitive markets. This explanation is well-aligned with Rogers'[22] classic theory of innovation adoption, whereby innovators have a higher tolerance for risk in part because of their greater financial resources. A final possibility is that TAVR may not have been an attractive additional service for interventional cardiology groups in competitive markets, since from the practice's perspective it was unclear whether the monetary and nonmonetary (ie, prestige) benefits of offering TAVR outweighed the opportunity costs of providing the service.

Managed Care Penetration and Transcatheter Aortic Valve Replacement Adoption

The association between managed care penetration and TAVR adoption was also unexpected because prior studies found that managed care slows the adoption of new technology, potentially because managed care enhances competition on price rather than high-technology services.[23–26] However, for TAVR, it is possible that the increased coordination of care in markets with higher managed care penetration facilitated partnerships among hospitals, cardiologists, and surgeons that were necessary to provide TAVR.

Comparisons With Prior Findings

Empirical studies supporting the Medical Arms Race theory have largely focused on the actions of hospitals. Robinson and Luft[10] determined that hospitals in competitive environments more frequently adopted high-cost technologies such as magnetic resonance imaging. Kessler and McClellan[8] subsequently found that hospitals similarly adopted higher cost therapies for care of acute myocardial infarction in localities with greater competition. More recently, Devers et al[6] found evidence of competition encouraging technology adoption, and Berenson et al[5] found similar practices among hospital service lines. Our study differs from the majority of the existing literature by our focus on physician groups, and because of the unique policies governing the adoption of TAVR implemented by CMS, the dominant national payer because TAVR in 2012–2014 was primarily a technology used in elderly patients. Strobel et al[27] examined TAVR adoption in 5 states and found that higher hospital competition was associated with more rapid adoption. Our findings for hospitals were concordant with these prior findings—we also observed that hospitals in competitive markets nationwide adopted TAVR more readily. However, physician group practices behaved differently.

Limitations

It is appropriate to acknowledge several limitations to the current study. The internal validity of our use of TINs to indicate physician group affiliation ignores the possibility of multiple TINs being part of a single organization, hence the true number of independent groups is likely smaller than our analyses assume. Similarly, accurate measurement of TAVR adoption by physician groups with extremely high managed care penetration among their Medicare patients may have been impeded because our detection of TAVR adoption depended on the existence of Part B (ie, fee-for-service claims), which are not generated for Medicare Advantage enrollees. However, this would be expected to bias the findings toward lower adoption rates in high Medicare Advantage areas, rather than the higher rates that we observed. Our study did not incorporate the construct of "vertical integration," that is, physician group practices being acquired by hospitals and health systems during 2011–2014,[28] and this phenomenon could have influenced the relationship between physician group competition and TAVR adoption. Finally, the uniqueness of policies governing TAVR adoption affects our

TABLE 2. Multivariate Regression Results: Hazard Ratios for TAVR Adoption

Characteristics	Hazard Ratio (95% CI)		
	Model 1: Market Characteristics	**Model 2: Market and Practice Characteristics**	**Model 3: Market, Practice, and County Characteristics**
Market characteristics			
Population (log scale)	2.40 (1.69–3.41)***	1.69 (1.15–2.47)**	1.62 (1.06–2.49)*
Physician group practice HHI[†]	1.26 (1.17–1.36)***	1.28 (1.19–1.38)***	1.26 (1.16–1.37)***
Hospital HHI[†]	0.84 (0.79–0.90)***	0.87 (0.81–0.93)***	0.93 (0.85–1.01)
Practice characteristics			
Mean HCC risk[‡]	—	0.97 (0.81–1.16)	1.03 (0.85–1.24)
Case volume	—	1.03 (1.02–1.03)***	1.03 (1.02–1.03)***
Academic hospital affiliation	—	3.07 (2.44–3.85)***	2.52 (2.00–3.19)***
TAVR hospital affiliation[§]	—	21.5 (11.8–39.2)***	20.4 (10.8–38.5)***
County characteristics			
Medicare managed care penetration[‖]	—	—	1.28 (1.17–1.40)***
Percentage change in managed care penetration[¶]	—	—	1.52 (0.95–2.44)
Urban county[#]	—	—	1.62 (0.78–3.36)
Per capita income ($thousands)	—	—	0.99 (0.98–1.00)*
Persons over age 65 (%)	—	—	0.96 (0.93–1.00)*
Adults with a high school diploma (%)[††]	—	—	1.84 (1.50–2.27)***
Physicians per capita	—	—	1.01 (1.00–1.01)**
Hospital beds per capita	—	—	0.999 (0.997–1.001)
Coronary care unit hospital in county	—	—	3.07 (1.91–4.93)***

Data presented are hazard ratio for unit change in characteristic, with 95% CI in parentheses.

[†]Coded such that a unit change in the coefficient corresponds to a 1000 difference in HHI.

[‡]Mean HCC risk among all Medicare patients receiving treatment by interventional cardiologists in the physician group practice.

[§]Physician group affiliated with hospitals that participated in pre–Food and Drug Administration (FDA)-approval TAVR clinical trials.

[‖]Coded such that a unit change corresponds to a 10 percentage point difference in managed care penetration.

[¶]Percentage point change in Medicare managed care penetration from 2011 to 2014 at the county level, coded such that a unit change corresponds to a 10 percentage point change in managed care penetration.

[#]Urban counties indicated by being coded as a "1" on the 2013 US Department of Agriculture's Rural-Urban Continuum Coding Scheme (range: 1–9).

[††]Percentage of adults over age 25 in the county with a high school diploma according the American Community Survey (2011). A unit change reflects a 10 percentage point change in the percentage of adults with a high school diploma.

CI indicates confidence interval; HCC, Centers for Medicare and Medicaid Services Hierarchical Condition Category; HHI, Hirfindahl-Hirschman Index; TAVR, transcatheter aortic valve replacement.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

study's external validity, and thus our findings may not apply to the diffusion of other medical technologies, nor to more recent TAVR adoption since 2014.

CONCLUSIONS

The adoption of TAVR was more common in medical markets with a higher concentration of interventional cardiology physician groups. This finding challenges the standard "Medical Arms Race" assumption that competitive markets incentivize the adoption of advanced medical technology, ultimately leading to inappropriate medical resource use. Our findings suggest that the Medical Arms Race is not the governing paradigm in all cases of technology diffusion in fee-for-service environments. In fact, it is possible that physician group practices in highly competitive markets may have lacked the necessary CMS-imposed regulatory qualifications to provide TAVR expeditiously to patients who might have benefited from it.

REFERENCES

1. Mack MJ, Brennan JM, Brindis R, et al. Outcomes following transcatheter aortic valve replacement in the United States. *JAMA*. 2013;310:2069–2077.
2. Food and Drug Administration. Notice of premarket approval; 2011. Available at: www.accessdata.fda.gov/cdrh_docs/pdf10/P100041A.pdf. Accessed October 25, 2019.
3. Centers for Medicare and Medicaid Services. National Coverage Determination Decision Memo for Transcatheter Aortic Valve Replacement (CAG-00430N); 2012. Available at: www.cms.gov/medicare-coverage-database/details/nca-decision-memo.aspx?NCAId=257. Accessed October 25, 2019.
4. Centers for Medicare and Medicaid Services. Calendar Year 2012 Physician Fee Schedule (PFS) final rule; 2012. Available at: www.cms.gov/Medicare/Medicare-Fee-for-Service-Payment/PhysicianFeeSched/PFS-Federal-Regulation-Notices-Items/CMS1253669.html. Accessed October 21, 2019.
5. Berenson RA, Bodenheimer T, Pham HH. Specialty-service lines: salvos in the new medical arms race. *Health Aff (Millwood)*. 2006;25:w337–w343.
6. Devers KJ, Brewster LR, Casalino LP. Changes in hospital competitive strategy: a new medical arms race? *Health Serv Res*. 2003;38:447–469.
7. Karaca-Mandic P, Town RJ, Wilcock A. The effect of physician and hospital market structure on medical technology diffusion. *Health Serv Res*. 2017;52:579–598.
8. Kessler DP, McClellan MB. Is hospital competition socially wasteful? *Q J Econ*. 2000;115:577–615.
9. Robinson JC, Luft HS. The impact of hospital market structure on patient volume, average length of stay, and the cost of care. *J Health Econ*. 1985;4:333–356.
10. Robinson JC, Luft HS. Competition and the cost of hospital care, 1972 to 1982. *JAMA*. 1987;257:3241–3245.
11. Luft HS, Garnick DW, Hughes RG, et al. Hospital competition, cost, and medical practice. *J Med Pract Manage*. 1988;4:10–15.
12. Bates LJ, Mukherjee K, Santerre RE. Market structure and technical efficiency in the hospital services industry: a DEA approach. *Med Care Res Rev*. 2006;63:499–524.

13. Birkmeyer JD, Stukel TA, Siewers AE, et al. Surgeon volume and operative mortality in the United States. *N Engl J Med.* 2003;349:2117–2127.
14. Kilic A, Shah AS, Conte JV, et al. Operative outcomes in mitral valve surgery: combined effect of surgeon and hospital volume in a population-based analysis. *J Thorac Cardiovasc Surg*. 2013;146:638–646.
15. Centers for Medicare and Medicaid Services. Hierarchical Condition Category 2006–2011 Model Software/ICD-9-CM Mappings; 2011. Available at: www.cms.gov/Medicare/Health-Plans/MedicareAdvtgSpecRateStats/Risk-Adjustors-Items/Risk2006-2011.html?DLPage=2&DLEntries=10&DLSort=0&DLSortDir=descending. Accessed October 18, 2019.
16. Adams DH, Popma JJ, Reardon MJ, et al. Transcatheter aortic-valve replacement with a self-expanding prosthesis. *N Engl J Med*. 2014;370:1790–1798.
17. Smith CR, Leon MB, Mack MJ, et al. Transcatheter versus surgical aortic-valve replacement in high-risk patients. *N Engl J Med*. 2011;364:2187–2198.
18. The Center for the Evaluative Clinical Sciences, Dartmouth Medical School. *The Dartmouth Atlas of Health Care, 1999*. Chicago, IL: American Hospital Publishing; 1999.
19. Fulton BD. Health care market concentration trends in the united states: evidence and policy responses. *Health Aff (Millwood)*. 2017;36:1530–1538.
20. Gowrisankaran G, Town RJ. Competition, payers, and hospital quality. *Health Serv Res*. 2003;38:1403–1421.
21. Jacobson GDA, Neuman T. A dozen facts about Medicare Advantage; 2018. Available at: www.kff.org/medicare/issue-brief/a-dozen-facts-about-medicare-advantage/. Accessed November 19, 2019.
22. Rogers EM. *Diffusion of Innovations*, 5th ed. New York, NY: Free Press; 2003.
23. Baker LC, Phibbs CS. Managed care, technology adoption, and health care: the adoption of neonatal intensive care. *Rand J Econ*. 2002;33:524–548.
24. Baker LC, Wheeler SK. Managed care and technology diffusion: the case of MRI. *Health Aff (Millwood)*. 1998;17:195–207.
25. Ramsey SD, Hillman AL, Pauly MV. The effects of health insurance on access to new medical technologies. *Int J Technol Assess Health Care*. 1997;13:357–367.
26. Ramsey SD, Pauly MV. Structural incentives and adoption of medical technologies in HMO and fee-for-service health insurance plans. *Inquiry*. 1997;34:228–236.
27. Strobel RJ, Likosky DS, Brescia AA, et al. The effect of hospital market competition on the adoption of transcatheter aortic valve replacement. *Ann Thorac Surg*. 2020;109:473–479.
28. Song Z, Wallace J, Neprash HT, et al. Medicare fee cuts and cardiologist-hospital integration. *JAMA Intern Med*. 2015;175:1229–1231.