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THE NATURE OF SURGEON HUMAN CAPITAL DEPRECIATION

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ABSTRACT

To test how practice interruptions affect worker productivity, we estimate how temporal breaks affect surgeons' performance of coronary artery bypass grafting (CABG). Using a sample of 188 surgeons who performed 56,315 CABG procedures in Pennsylvania between 2006 and 2010, we find that a surgeon's additional day away from the operating room raised patients' inpatient mortality risk by up to 0.067 percentage points (2.4% relative effect) but reduced total hospitalization costs by up to 0.59 percentage points. In analyses of 93 high-volume surgeons treating 9,853 patients admitted via an emergency department, where temporal distance effects are most plausibly exogenous, an additional day away raised mortality risk by 0.398 percentage points (11.4% relative effect) but reduced cost by up to 1.396 percentage points. These estimates imply a cost per life-year saved ranging from $7,871 to $18,500, rendering additional treatment intensity within surgery cost-effective at conventional cutoffs. Our findings are consistent with the hypothesis that after returning from temporal breaks surgeons may be less likely to recognize and address life-threatening complications, in turn reducing resource use. This form of human capital loss would explain the decrease in worker productivity and the simultaneous reduction in input use.

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I. Introduction

Fluctuations of human capital and worker productivity have been the subject of a long literature stretching back to Ben-Porath (1967). This early work on human capital and productivity spurred multiple lines of inquiry. One of these has focused on organizational forgetting, in that a firm's productivity may erode because its workers' human capital decays or because of turnover or breaks in production (Argote, 1999, Darr, Argote and Epple, 1995; Benkard 2000; Thompson 2007, David and Brachet, 2009 & 2011).

Previous research has measured the reduction in individual worker productivity when the temporal distance between tasks increases. These reductions have been documented for jobs with routine tasks ranging from data entry (Globerson Levin and Shtub, 1989) to mechanical assembly (Bailey, 1989) and car radio production (Shafer, Nembhard, and Uzumeri, 2001). Recent work has focused on more complex tasks arising in the provision of health care. These studies suggest temporal distance effects may substantially impact patient outcomes in surgery (Hockenberry, Lien and Chou, 2008) and in the delivery of emergency medical services (David and Brachet, 2011).

In this paper we make three contributions. First, we develop a framework for distinguishing between two mechanisms that explain how a decline in surgeon human capital, measured here as increased temporal distance, might impair surgeon productivity, measured here as patient outcomes. Previous literature has documented that organizational and individual skill depreciation between performing temporally distant tasks adversely affects health care outcomes, but the underlying mechanism has not been established (Hockenberry, Lien and Chou, 2008; David and Brachet, 2011).

Increasing temporal distance could lead to either inefficient care or inattentive care. After temporal breaks, surgeons may fail to identify and treat life-threatening complications (inattentive care). For instance, surgeons may be less likely to notice small but potentially life-threatening anomalies during surgery that require additional tests or procedures to ensure the patient's survival. This form of human capital depreciation will reduce the patient's survival probability and at the same time *reduce* resource use.

Alternatively, temporal breaks may erode surgeons' proficiency and thus prompt them to apply more treatment (inefficient care). For instance, surgeons may take longer to complete a given procedure or compensate for lower proficiency with additional testing and procedures. This form of human capital depreciation will *raise* the surgeon's resource use without raising the patient's survival probability.

We observe the resource use and survival probabilities of patients undergoing coronary artery bypass grafting (CABG) and thus can distinguish between these two forms of surgeon human capital depreciation empirically. We find that the time since the surgeon last performed the procedure raises peri-procedural mortality in a clinically meaningful and statistically significant way. The temporal distance effects are lasting in that they also predict in-hospital mortality. We also find that temporal distance is associated with reduced resource use. This pattern is consistent with the hypothesis that temporal breaks lead to inattentive care in that surgeons tend to miss altogether and therefore fail to address life-threatening complications, rather than notice but address them less efficiently. Policies that affect surgeons' procedure schedules may reduce operative mortality for patients undergoing coronary revascularization but they may also raise cost.

Second, we test and compare how two measures of temporal distance affect surgeon performance. We examine both the impact of the number of days since the surgeon last performed CABG surgery, which captures the effect of depreciation in procedure-specific human capital, and the impact of the number of days since the surgeon performed *any* procedure, which proxies for depreciation in general surgical human capital.[1] Our empirical results suggest that general surgical human capital affects patient outcomes substantially more than procedure-specific human capital.

Finally, we exploit the variation in resource use induced by variation in temporal distance to measure the productivity of additional medical spending on the margin. Our back-of-the-envelope calculation suggests that the cost per life-year saved resulting from more attentive, and thus intensive treatment within a chosen procedure, ranges from $7,400 to $17,500, in line with other recent estimates (Doyle, 2005 & 2011; Chandra and Staiger 2007; Almond, Doyle, Kowalski and Williams, 2010) and well below the conventional $100,000 per life-year threshold (Cutler, 2004).

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[1] We examined the frequency distributions of the other procedures and found those that are typically performed by the surgeons who perform CABG include heart valve procedures, procedures on thoracic vessels (other than bypass), and device implants.

2. Background

2.1 *Background on human capital depreciation*

There is an extensive literature in industrial engineering that seeks to establish the degree of human capital depreciation, also referred to as forgetting, in productive tasks. Several studies have examined the speed of human capital depreciation by randomizing individuals engaged in a repetitive task, ranging from breaks of one day to a few weeks to even a few months (Globerson, Levin and Shtub, 1989; Bailey, 1989: Shafer, Nembhard and Uzumeri, 2001). Worker productivity declined a few percentage points after an interruption lasting a single day (Globerson, Levin and Shtub, 1989) and increased at an increasing rate with each additional day of interruption (Jaber, 2011).

While studies of human capital depreciation in manufacturing settings have focused on the performance of repetitive tasks, they have ignored more complex cognitive tasks like those often found in health care delivery. For instance, highly variable “inputs” in health care delivery, such as each patient’s individual anatomy and disease progression profile, differ from the largely homogeneous inputs found in manufacturing. Thus healthcare delivery, and in our case surgery, places significant demands on workers’ cognitive skills. Earlier work examined how breaks in the performance of cardiac surgery affect patient outcomes, arguing that these outcomes reflect productivity differences (Hockenberry, Lien and Chou, 2008). For CABG surgery in Taiwan, the authors estimated that relative to a 0-2 day break, a break from performing CABG of 3-14 days raised mortality by 11-14%, and a break of more than 15 days raised mortality by 22%.

That study only measured temporal distance between performing CABG procedures. Yet, studies on forgetting suggest that other activities in which workers engage during breaks from the productive task of interest may play an equally important role in human capital depreciation (Jaber, 2011). In our context, many surgeons will perform other procedures, such as isolated heart valve procedures and other vascular procedures that require the same cognitive skill set as CABG and that therefore may slow the rate of skill depreciation between CABG procedures. Thus, to the extent that Hockenberry et al. did not account for the performance of skill-preserving tasks between the CABG surgeries they observed, their results would underestimate the true effect of skill depreciation on surgeon productivity. In this paper, we contrast the performance effects of the number of days since the surgeon last performed CABG with the performance effects of the number of days since the surgeon performed any procedure to assess the role of CABG-specific skill components in explaining the productivity loss after temporal breaks.

2.2 The performance and organization of CABG

Coronary artery bypass graft (CABG) is a major surgical procedure intended to improve the heart's supply with oxygen. A surgeon harvests part of a vessel from a different area of the body (typically the groin or chest wall), opens the chest cavity, and implants the harvested vessel segment to bypass the diseased section of the artery. CABG surgery takes approximately four hours and patients generally spend at least one week recovering in the hospital. In some cases the patient will also need a concomitant valve replacement or repair procedure, which lengthens surgery time further (Hockenberry et al, 2011).

3. Methods

3.1 Empirical model

We assume that a surgeon's human capital Q_0 decays exponentially over time at rate δ (Rubin and Wenzel, 1996; Kahana and Adler, 2012):

$$Q(t) = Q_0 e^{-\delta t}.$$

or

$$\ln Q(t) = \ln Q_0 - \delta t \quad (1)$$

If we further assume that patient outcomes improve with human capital, (1) predicts that a surgeon's longer temporal break will reduce patient survival.

Our proxy for the current stock of human capital $Q(t)$ is based on the literature on organizational learning and forgetting.[2] This literature has shown that past production experience impacts productivity (Argote, Beckman and Epple, 1990; Benkard, 2000), which in our setting would be reflected in increased survival. These studies also conclude that the stock of past production experience will depreciate with t, the time since it was accumulated (Argote, Beckman and Epple, 1990; Benkard, 2000). This form of organizational forgetting is thought to be tied, at least in part, to individual worker human capital decay (David and Brachet, 2011). Furthermore, a long literature indicates that provider quality is a function of experience, specifically there is a relationship between a provider's volume of procedures and patient outcomes (Luft, Bunker,

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[2] The lifetime stock of accumulated capital and its depreciation will be captured empirically by individual fixed effects and surgeons' years of experience, measured by the time since they graduated from medical school. In line with the industrial engineering literature on forgetting, we focus here on the short-term fluctuations of this stock.

Enthoven, 1979; Luft, Hunt and Maerki, 1987; Halm, Lee and Chassin, 2003; Gaynor, Seider and Vogt, 2005: Hockenberry, Lien and Chou, 2010).[3]

Thus we estimate the following equation:

$$m_{i,j,k,y} = \beta_0 + \beta_1 \ln(\text{hospital volume})_{i,j} + \beta_2 \ln(\text{surgeon volume})_{i,k} + \beta_3 \text{ days since last procedure}_{i,j} + \beta_4 X_i + \rho_j + \varphi_k + \psi_y + \varepsilon_{i,j,k,y} \quad (2)$$

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[3] There is disagreement on whether this is due to patients sorting to better providers (selective referral) or whether experience itself in the form of volume actually improves outcomes (practice makes perfect). Our identification strategy is based on the inclusion of hospital and surgeon fixed effects, ρ_j and φ_k respectively. All the hospitals and nearly all the surgeons in our data were performing CABG on patients prior to the start of our study period. Thus we argue that hospital and surgeon fixed effects control for provider quality that has been revealed to the market at the start of the study period. Furthermore, in the case of the depreciation effect, any positive selection effect where an increased demand for a surgeon's service is attributable to unobserved surgeon characteristics is likely to bias the estimate of the temporal distance effect, represented by β_3 in equation (2), toward zero. Pennsylvania has a public report card system for both hospitals and surgeons performing CABG, which appears to steer patients away from poorly performing and low-volume surgeons (those performing fewer than 30 procedures annually) whereas distance from home is the main driver of hospital choice (Wang, Hockenberry, Chou and Yang, 2011; Epstein, 2010). There is little variation in these report cards over time. Nevertheless we conducted robustness checks by including recent report card information in our specifications. The effects of report cards on mortality were not precisely estimated, and did not change the coefficients or statistical significance of our temporal distance measures.

where $m_{i,j,k,y}$ is a mortality indicator for patient i at hospital j whose procedure was performed by surgeon k in calendar year y. Hospital and surgeon volume are measured as the volume in the year leading up to and including the procedure on the patient surgeon k operated on just before operating on patient i.[4] X are the observable characteristics of patient i including gender, race, age, source of insurance coverage and comorbidities. Each of our models also includes hospital and surgeon fixed effects, ρ_j and φ_k, as well as year fixed effects, ψ_y.

The coefficient β_3 for "days since last procedure" is the empirical estimate of δ; it captures the depreciation of human capital, measured by its effect on the patient's mortality risk, due to increased temporal distance since CABG or any surgical procedure was last performed by the patient's surgeon. Since we measure time as the number of days since last performing CABG or any procedure, β_3 is the effect of an additional elapsed day on the patient's probability of death, and is expected to be positive. To distinguish between depreciation in procedure-specific and general surgical human capital, we estimate separate models in which we define temporal distance as the number of days since last performing CABG or last performing any inpatient procedure. We estimate linear probability models and cluster the standard errors at the surgeon level to account for within-surgeon correlation of the disturbances across procedures.

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[4] By construction, temporal distance and surgeon volume will be correlated. The correlation between surgeon volume and time since the surgeon last performed CABG was -.21. The correlation between surgeon volume and time since the surgeon last performed any inpatient procedure was -.12. We estimated specifications of our models excluding surgeon volume with nearly identical results.

To distinguish between the two competing forms of surgeon human capital depreciation (inattentive care versus inefficient care), we model the total cost C of treating a patient whose health and socio-demographic characteristics at the time of admission are represented by x and whose surgeon last performed a procedure t days ago:

$$C(t, x) = a(x) + p(x)r(t)c(t)$$

where a is the fixed cost of performing the procedure, p is the probability that the patient will suffer a life-threatening complication during the procedure, r is ratio of the potential complications the physician observes and treats successfully, and c is the effort and time cost to the surgeon of addressing the complication. In line with our model of inattentive care we assume that r decreases with t: $r' < 0$. Thus, the patient's mortality risk is $p(1-r)$ and an increase in the surgeon's time away will increase the patient's mortality risk by $-pr' > 0$. In line with our model of inefficient care, we assume that the cost of addressing a complication c increases with the time since the last procedure t: $c' > 0$.

A priori the effect of time away from the operating room on total cost is ambiguous:

$$C_t = p[\, r'c + rc'].\ (6)$$

The first term in brackets, $r'c < 0$, represents "inattentive care" resulting from increased temporal distance: the surgeon will be less likely to spot, and consequently address successfully, a life-threatening complication, thus raising mortality but reducing cost. The second term in brackets, $rc' > 0$, represents "inefficient care" resulting from increased temporal distance: the surgeon will expend more resources to rescue the patient and thus raise cost without raising mortality. Our data allow us to assess empirically which of these effects dominates.

To obtain empirical estimates of the impact of temporal distance on resource use we estimate the following equation:

$$\ln(\text{costs})_{i,j,k,y} = \beta_0 + \beta_1 \ln(\text{hospital volume})_{i,j} + \beta_2 \ln(\text{surgeon volume})_{i,k} + \beta_3 \text{ days since last procedure}_{i,j} + \beta_4 \text{ mortality} + \beta_5 X_i + \rho_j + \varphi_k + \psi_y + \varepsilon_{i,j,k,y} \quad (7)$$

where costs are total inpatient costs.[5] An indicator for the patient's death before discharge (in-hospital mortality) is included to avoid conflating differences in charges with differences in patient mortality outcomes. All other covariates are defined as in the mortality model (2).

3.2 Robustness Checks

Increases in temporal distance could be correlated with unobserved determinants of patient survival or hospital charges and thus endogenous. For instance, surgeons aware of and concerned about skill depreciation might select relatively healthier patients to operate on immediately after returning to work, in which case our mortality estimates would understate the true impact of temporal breaks and any reduction in cost would be explained at least in part by patient selection. If, on the other hand, surgeons returning to work triage patients in that they operate first on those patients who are at highest risk of death, our mortality estimate will overstate the true effect. To mitigate this endogeneity concern, we perform a series of robustness checks.

As a first robustness check, we restrict the sample to patients who were admitted emergently and thereby reduce further the possibility that selection on unobservables may be driving the results.[6]

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[5] We also estimated models where we looked at post-operative length of stay, a more objective measure of resource use, and found the results to be consistent with the charges results.

When patients are admitted emergently, surgeons have little scope for patient selection, thereby mitigating the effect of unobserved patient heterogeneity in confounding the measured effect of temporal distance on outcomes. Moreover, as emergently admitted patients are typically more acutely ill than electively admitted patients, the mortality outcomes for emergently admitted patients should be particularly sensitive to surgeon skill and thus to the time since last performing CABG or any inpatient procedure.

As a second robustness check, we restrict the sample to CABGs performed by surgeons performing at least 100 CABG procedures per annum. This is the threshold used by the Leapfrog Group, a coalition of large health care purchasers, to define high procedures volumes, which are thought to improve performance. This robustness check mitigates the possibility that the temporal distance effect could be confounded by systematic unobservable quality differences between high and low volume surgeons and the severity of the patients they treat.[7]

Third, we test if temporal distance predicts differences in observable patient characteristics that are likely correlated with unobserved patient severity or complexity. Specifically, we test

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[6] The Pennsylvania claims data we use indicate whether the patient's procedure was emergent, urgent or elective. These classifications are based on clinical criteria established by the National Uniform Billing Committee.

[7] We also estimated models with interaction terms for volume and temporal distance to differentiate between the effects of volume and temporal distance directly. However, the coefficients on the volume term and the interaction term were not significant. This could indicate that low-volume surgeons typically treat otherwise healthier patients, which would mute possible the inattention effects for that group.

whether temporal distance was is correlated with the number of patient comorbidities and with the probability that the patient was admitted with acute myocardial infarction (AMI), a common marker of patient complexity.

3.3 Data

We use the Pennsylvania Inpatient Hospital Discharge Data from the Pennsylvania Health Care Cost Containment Council (PHC4) from the third quarter of 2006 through the fourth quarter of 2010. The PHC4 data include patients' demographic characteristics, insurance coverage, comorbid conditions as captured by the International Classification of Diseases, Ninth Revision Clinical Modification (ICD-9CM) codes, hospital identifiers, and surgeons' license numbers. From these data we identify all adults (age 18 years or older) undergoing CABG in Pennsylvania hospitals using relevant procedure codes.[8]

3.3.1 Outcomes

We estimate the effect of the surgeon's temporal break on two dimensions of performance: the patient's risk of death during hospitalization, and the natural logarithm of total hospitalization cost. We use two mortality measures as proxies for overall procedure quality[9]: peri-procedural mortality, defined as death within one day of the procedure, and in-hospital mortality, defined as death at any time before discharge. The PHC4 data include hospital charges, which we convert to cost using Medicare cost-to-charge ratios.

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[8] ICD-9 CM procedure codes 36.10-36.17 and 36.19.

[9] The standard 30-day mortality measure is not available in these data because we only have information through discharge from the current admission, and most patients are discharged within a week of the procedure.

3.3.2 Time Since Last Procedure

We measure the covariate of interest, the time since the surgeon last performed surgery, in two ways: the number of days since the surgeon last performed a CABG procedure and the number of days since the surgeon last performed any inpatient procedure. PHC4 used restricted date-of-procedure data to construct an additional variable coded as the number of days since the operating physician was last listed as the operating physician for any inpatient procedure and a variable indicating the sequence of all the records for which a physician was listed as the operating physician.[10]

3.3.3 Provider Characteristics

We include hospital CABG volume and surgeon CABG volume. Both volume measures are defined as the number of CABG procedures performed at the hospital or by the surgeon during the 365 days leading up to each procedure included in the sample. We also include categorical variables for hospital size (beds) and each physician's years of experience, defined as the number of years since graduation from medical school at the time of the procedure.

3.3.4 Patient and Discharge Characteristics

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[10] This was provided to us upon request from PHC4. In order to get access to this variable, PHC4 had to remove day of week information from the data to limit the risk identification of patients, and we are therefore unable to consider day of the week effects. However, Hockenberry Lien and Chou (2008) examined this issue and found that "weekend effects" did not explain the temporal distance effect on mortality.

Patient-level independent variables include patient age in years, gender, race/ethnicity indicators, and primary payer (private payer, Medicare, Medicaid, uninsured). To capture the effect of co-morbidities that might affect the outcome independently of the surgeon's time since last procedure, we also include a comorbidity index developed by Elixhauser et al. (1998), the number of vessels bypassed (indicator variables from 1 to 4 or more), the type of admission (elective, urgent, or emergent), an indicator that the admitting diagnosis was acute myocardial infarction (AMI), and the number of days from patient admission to procedure (to capture the effects of patients who were frail enough to require hospitalization for stabilization before the procedure, or who were admitted for unrelated reasons and the vascular occlusion was subsequently discovered). We also include indicators that the procedure included cardiopulmonary bypass and that it included a concomitant valve procedure, as both indicate potentially more complex procedures and more time under anesthesia, which in turn could affect outcomes.

4. Results

4.1 Provider and Patient Characteristics

The study sample includes 56,315 discharges, 188 surgeons, and 62 hospitals. Mean 1-day mortality was 0.62%, mean in-hospital mortality was 2.72%, and average total cost was $35,343. For surgeons performing at least 100 CABG procedures per annum, mean 1-day mortality was 0.52%, mean in-hospital mortality was 2.47% and total cost was $32,900, consistent with the hypothesis that high-volume providers are more efficient and effective. As would be expected, emergently admitted patients had higher mortality rates and cost, and the procedures performed by high-volume surgeons on this group again resulted in lower mortality and lower cost (Table 1).

The mean number of days since last performing any inpatient procedure was 1.99 for all surgeons and 1.52 for high-volume surgeons. The number of days since last performing CABG was 3.96 for all surgeons and 2.64 for high-volume surgeons. Figures 1 and 2 show the distributions of the two measures of temporal distance for all physicians in the sample. Figure 3 shows the mean number of comorbid conditions among patients as a function of the number of days since their surgeon last performed any inpatient procedure. Given the nature of the condition and the procedure, most patients were elderly and covered primarily through Medicare. Seven in ten patients were male and nearly ninety percent were white (Table 1).

4.2 The Effect of Temporal Breaks on Mortality

In the full sample, an additional day without performing any inpatient procedure was associated with an increase in 1-day mortality by nearly 0.05 percentage points, or 7.4% relative to the sample mean (Table 2). The absolute effect on in-hospital mortality was larger at nearly 0.07 percentage points, but on a relative basis it was smaller, 2.5%. The effect was smaller in relative magnitude and not statistically significant when temporal distance was defined as days since last CABG rather than last inpatient procedure.

The estimated impact of days since last inpatient procedure on mortality was larger in the restricted samples. Among emergent patients (Table 2), an additional day increased 1-day mortality by .11 percentage points (12.5%) and in-hospital mortality by .20 percentage points

(5.0%). Compared to 1-day mortality, temporal breaks had a larger absolute effect on in-hospital mortality but their magnitude relative to in-hospital mortality was smaller.

Among all patients whose CABG was performed by a high-volume surgeon (Table 2), an additional day away from the OR increased 1-day mortality by 0.09 percentage points (a 17.5% relative effect) and in-hospital mortality by 0.17 percentage points (a 6.8% relative effect). In contrast to the results for the full sample, a one-day increase in time since CABG also significantly increased 1-day mortality by .03 percentage points and in-hospital mortality by .08 percentage points, effects that were still smaller in magnitude than the impacts from an additional day since any inpatient procedure.

Finally, among emergently admitted patients whose CABG was performed by a high-volume surgeon (Table 2), an additional day away from the OR increased 1-day mortality by 0.22 percentage points (31.5%) and in-hospital mortality by nearly a 0.40 percentage points (11.44%). Again, a one day increase in time since CABG also significantly increased 1-day mortality by nearly 0.08 percentage points and in-hospital mortality by nearly 0.21 percentage points, effects that were still smaller in magnitude than the impacts from an additional day since any inpatient procedure.

4.3 The Effect of Temporal Breaks on Costs

In the full sample, an additional day without performing any inpatient procedure was associated with a statistically significant decrease in total cost of about 0.6 percent, or nearly $210 (Table 3). Consistent with the results for patient mortality, the reduction was only 1/6 as large at 0.1

percent, or $36, for an additional day since last performing CABG. In the case of emergently admitted patients an additional day away from the OR reduced cost by about 0.8 percent, or about $329. Again the impact was generally smaller when temporal distance was defined as the number of days since last performing CABG, at 0.1 percent.

Finally, among those treated by a high volume surgeon, an additional day without performing any inpatient procedure was associated with a statistically significant decrease in total cost of about 1.1 percent, or nearly $349 (Table 3). The reduction was only 40% as large for an additional day since CABG at 0.4 percent, or $141. In the case of emergently admitted patients treated by high volume surgeons, an additional day away from the OR reduced cost by about 1.4 percent, or about $518. Again, the impact was generally smaller when temporal distance was defined as the number of days since last performing CABG, at 0.4 percent.

4.4 Robustness checks

To test whether there was evidence that our temporal distance effects were the result of selection bias, we estimated a set of additional regression equations. If observed patient comorbidity or the probability of the patient having an AMI at admission were associated with temporal distance, this would indicate some patient selection. The results of these estimations are reported in Table 4. As is evident, none of the point estimates of the effect of temporal distance on patient comorbidity or AMI are precisely estimated, nor are they clinically significant. Since comorbidity represents one of the main characteristics a surgeon would use to engage in selection behavior, it is unlikely that our effects are driven by selection.

4.5 The Implied Cost of Saving an Additional Life-Year

We use the simultaneous increase in mortality and decrease in cost associated with increased temporal distance to calculate the implied cost of saving an additional year of life. In Table 5 we summarize the previous results and derive the implied cost per life-year saved for each subsample. Specifically, we reproduce the percentage-point reduction in in-hospital mortality associated with a shortening the temporal distance (defined as time since last inpatient procedure) by one day and translate the mortality reduction into the implied increase in life expectancy assuming that patients could expect to live an additional 17.6 years after surviving CABG (van Domburg, Kappetein, and Bogers, 2009). The resulting cost per life-year saved ranges from $7,871 to $18,500.

5. Discussion

We find that, after accounting for patient and provider characteristics, an additional day since the surgeon's last inpatient procedure raised peri-procedural mortality of CABG patients on average by 7.4% and in-hospital mortality by 2.5%. Hockenberry, Lien and Chou (2008) found that the impact of increasing time away to be monotonically increasing, so the implied cumulative effect of several days away from the operating room on outcomes could be substantial. The large effects we observe here are likely attributable to differences in how temporal distance was measured. The earlier work used a reference group of 0-2 days and compared procedures grouped into 2-14 day and 15+ day breaks. However, learning theory suggests that forgetting follows an exponential or power function path. As such, the largest reductions in human capital would occur in the first few of days.

In the data used here, most procedures were performed by surgeons who had been in the operating room in the last 7 days. One might ask whether we expect surgeons to experience skill depreciation so quickly. In fact, the industrial engineering literature suggests the depreciation is quite rapid, and continues out for months. The more recent literature also finds that this depreciation effect is independent of how quickly or how much learning was accumulated (Jaber, 2011).

In this study, the data did not allow us to parse out which of the multiple skills that surgeons use to perform CABG procedures were depreciating and how rapidly. They could be primarily cognitive in nature and thus consistent with our hypothesis of inattentive care, which in turn is supported by the results we report here. They could also include dexterity or the ability to manage a surgical team. If it were possible to randomize surgeons to longer breaks from surgery and measure these different types of skill, then one could estimate more accurately skill-specific depreciation functions.

While temporal breaks raise mortality risk, we also find that they reduce the total cost of hospitalization, again consistent with the inattentive-care hypothesis.[11] The reduction in resource

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[11] Conceivably, the temporal-distance effects might be muted or even reversed for 30-day mortality. For instance, surgeons returning from relatively short breaks away from the operating room might also discharge patients sooner, i.e. before they die in-hospital. To test for this possibility, we estimated multinomial logit models but found no evidence that the number of days since performing any or a CABG procedure last was systematically associated with the patient's likelihood of being discharged to a skilled nursing facility rather than home. This

use after a practice interruption runs counter to studies of other settings, which found more inputs were needed to produce a given unit of output as human capital declined (Argote, Beckman and Epple, 1990; Benkard, 2000). However, the result is consistent with the hypothesis that surgeons returning from a temporal break may be more likely to miss complications that arise during or after the procedure. Surgeons who miss life-threatening complications raise their patients' mortality risk but they also use fewer resources than surgeons who notice and address these complications.

As in any study using administrative data, we were limited in the clinical information we could bring to bear in our risk adjustment. Even after controlling for surgeon fixed effects, endogenous scheduling of patients by severity may have confounded the estimates. For instance, surgeons may have scheduled electively admitted patients with the least (unobserved) risk of life-threatening complications to be treated after returning from longer temporal breaks. In this case, we would underestimate the effect of days between procedures on patient mortality. To the extent that unobserved patient characteristics on which the surgeons sort patients are correlated with the patient severity measures that we do observe in our data, sorting on observables reveals the likely extent of any bias imparted by unobserved heterogeneity (Altonji, Elder and Taber, 2005). In sensitivity analyses we examined the contribution of our clinical severity measures on the effects of temporal distance. The effect estimates without the severity controls were slightly

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finding is consistent with the fact that in our data the temporal distance effects for perioperative mortality are qualitatively identical to those for in-hospital mortality. Borzecki et al. (2010) also reported strong concordance between in-hospital and 30 day mortality across facilities for a variety of conditions..

smaller in magnitude than in the adjusted model but still statistically significant. Assuming high correlation between these observables and the unobserved severity characteristics, our estimates of the temporal-distance effects should be viewed as conservative.

We also did not find any systematic association between temporal distance and other markers of patient complexity, such as the number of comorbidities or the probability of having been admitted with acute myocardial infarction. This is perhaps not too surprising, as the organization of cardiac surgery and referral patterns vary widely across hospitals and markets, as do surgeons' affiliations with hospitals (Berenson, Ginsburg and May, 2006). Cardiac surgeons still take call with affiliated hospitals regardless of the employment relationship (i.e. employed by the hospital or independent).

In addition, the PHC4 data did not include the time of day that each procedure was performed. Thus, we had to use admission times to classify the first procedure of the day for the purpose of assigning temporal distance. To the extent that we measured temporal distance with error, our estimates would suffer from attenuation bias and again should be viewed as conservative. Sensitivity analyses that included an indicator for procedures performed on a day with other procedures did not materially change the estimated impact of temporal distance.

To minimize possible selection bias, we estimated the equations for the subsample of the approximately 3 out of every 10 patients who were admitted emergently. The emergent nature of the admission places a premium on timely decisions and interventions, which should be particularly sensitive to fluctuations in the surgeon's attention and application of skill. For these reasons, estimates based on this subset of patients should be less vulnerable to selection bias and more accurate in capturing the effect of temporal distance on mortality. For emergently admitted patients essentially all the sorting is determined by a call schedule which is fixed ex ante. Of course, it is possible that surgeons with below-average temporal-distance measures also succeed in securing slots on the call schedule during which emergently admitted patients are healthier on average. To minimize the confounding effect of this type of unobserved heterogeneity, we included surgeon and hospital fixed effects. For both mortality measures and both measures of temporal distance, we find larger effects on mortality and resource use.

As a second robustness check, we estimated the equations for the subsample of procedures performed by high-volume surgeons. High-volume surgeons would be expected to develop more effective routines than low-volume surgeons of maintaining their performance potential during a break and of regaining it after a break, resulting in a smaller estimated effect size. On the other hand, high-volume surgeons might be more likely to operate on patients with more complex, yet unobserved disease and therefore more likely to miss a life-threatening complication. This would be the case if low-volume providers are more selective and avoid emergently admitted patients, allowing them to treat patients who are healthier and more robust than the acutely ill patients treated by high-volume providers. Healthier patients are unlikely to die in the short term unless the procedure was performed very poorly. For these patients, mortality may be too coarse a measure to capture any temporal-distance effects on productivity. In addition, surgeons who perform only a few procedures a year are away from the operating room for more days on average than high-volume surgeons. Because our models include surgeon fixed effects, the departures from their best performance may not be as pronounced. On balance, we did not find statistically significant reductions in effect size for any of the measures of mortality and temporal breaks; to the contrary, for several specifications the effect size increased when the sample was limited to high-volume surgeons.

For patients who were admitted emergently and treated by a high-volume surgeon, extending the surgeon's temporal break by an additional day raised the patient's 1-day mortality risk by 31.5% and the in-hospital mortality risk by 11.4%.

In conclusion, we find that practice interruptions in the form of a surgeon's additional day away from the operating room raised patients' mortality risk by up to 0.4 percentage points but reduced the total cost of hospitalization by up to 1.4%.

Moreover, in both the outcome and spending models, the results were stronger when the temporal distance since last performing any inpatient procedure was used rather than temporal distance since last performing CABG. While an earlier study examined the temporal distance between specific procedures only (Hockenberry, Lien and Chou, 2008), our estimates suggest that the outcome and spending effects are largely accounted for by the depreciation of general surgical human capital rather than procedure-specific human capital. Thus surgeons who are performing other procedures between performing CABG appear to be able to maintain proficiency, which is important in an era of declining CABG volume.

Our findings also raise the question which policies might mitigate the adverse impact of temporal breaks on physician performance. If temporal breaks compromise focus or attention to possible complications, as our results suggest, greater reliance on other members of the surgical team and the use of surgical safety protocols and checklists may be warranted (Haynes, et al, 2009; Birkmeyer 2010, de Vries et al. 2010). Such interventions aimed at aiding surgeons regain their pre-break performance levels, along with changes in scheduling that reduce the average time away from the operating room, might be justified if they improve expected patient outcomes sufficiently. Our most conservative estimates imply that raising patients' pre-operative life expectancy by one year would raise costs by as little as $7,871, more than 25% less than the median cost per life-year saved reported by a well-known study of over 500 medical interventions (Tengs, Adams, Pliskin, et al, 1995).

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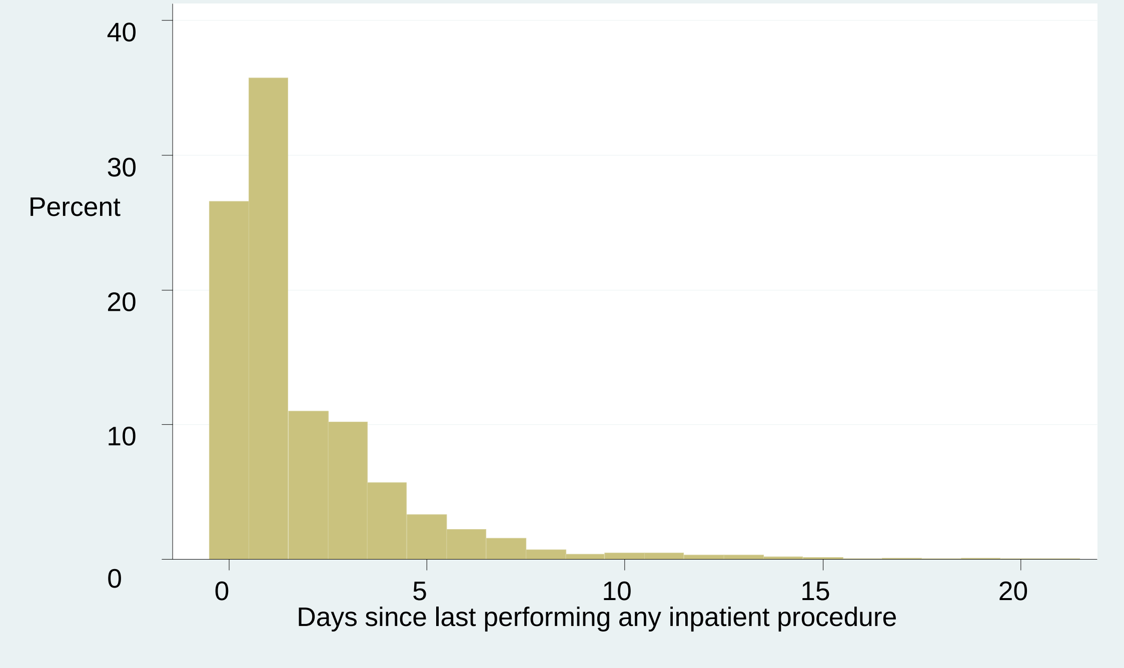


Figure 1. Distribution of CABGs

by days since surgeon last performed any inpatient procedure

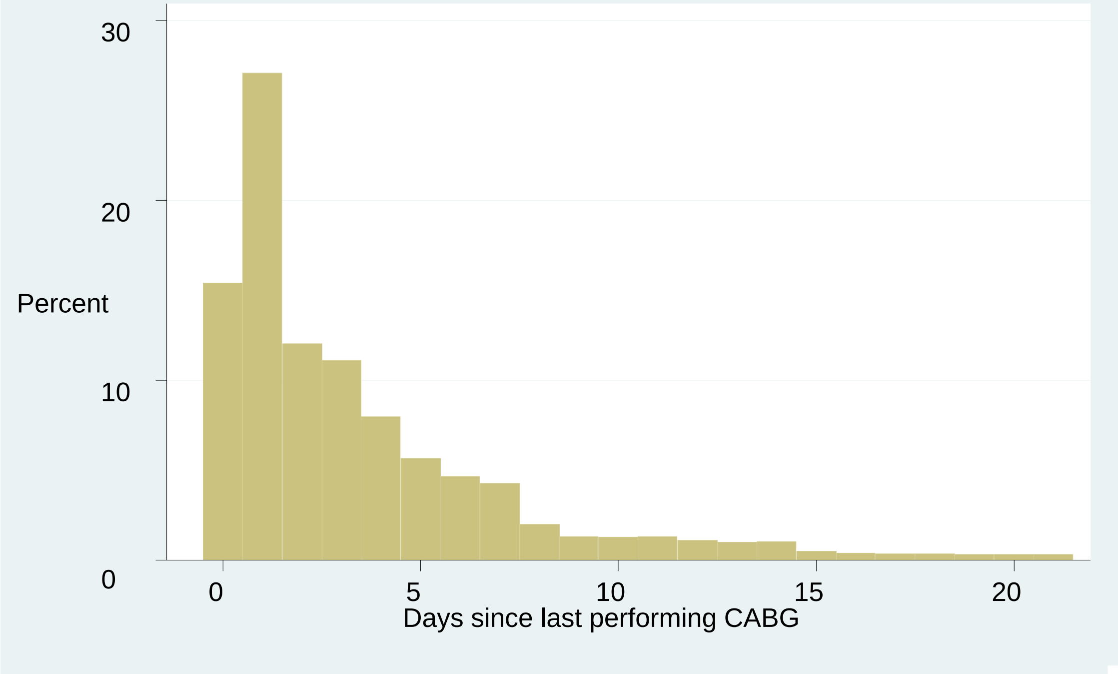
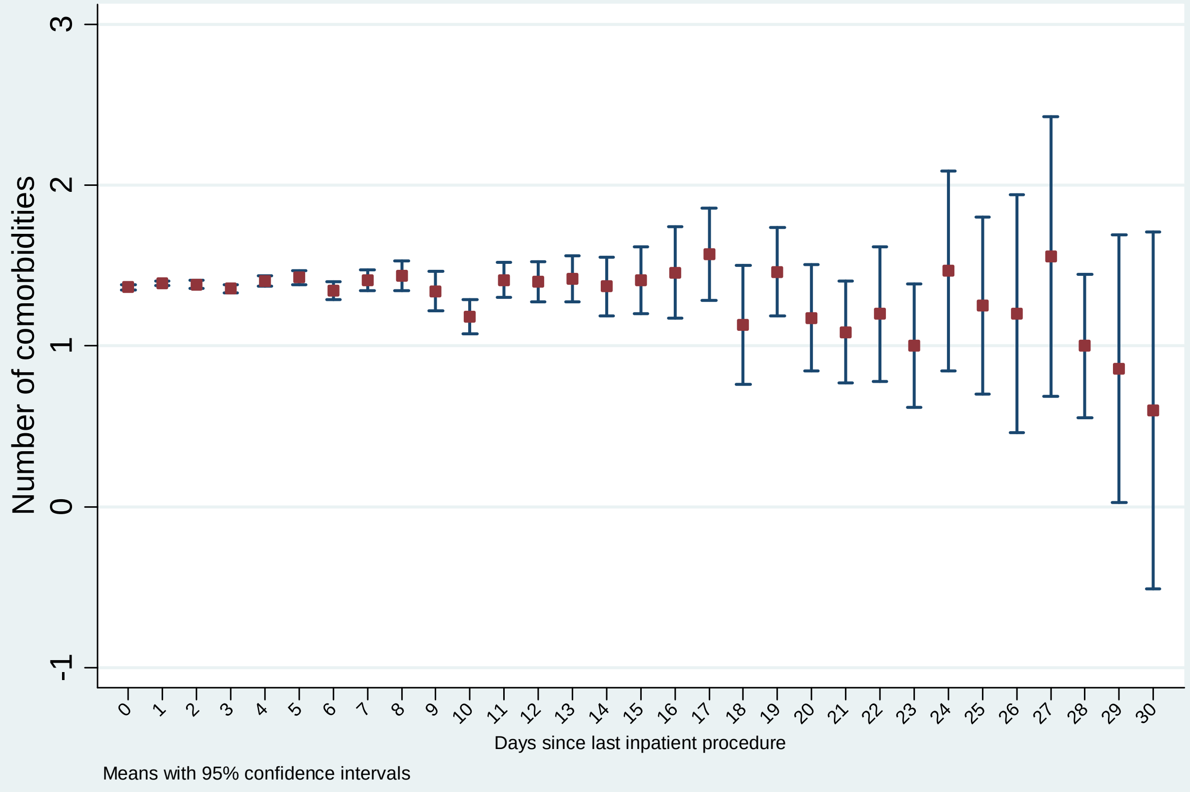


Figure 2. Distribution of CABGs

by days since surgeon last performed a CABG

Figure 3. Comorbidity burden of patients by surgeons days since last procedure



1. Comorbities are those derived from the index created by Elixhauser and colleagues (1998).

Table 1. Summary Statistics	Procedures performed by surgeons with annual volume of >11 CABGs		Procedures performed by surgeons with annual volume of >99 CABGs	
	All admissions	Emergent admissions	All admissions	Emergent admissions
	56,315	16,702	33,106	9,853
outcomes and cost				
1-day mortality (percent)	0.62	0.89	0.52	0.71
in-hospital mortality (percent)	2.72	3.95	2.47	3.48
total costs	$35,343	$40,166	$32,900	$37,107
provider characteristics				
days since last CABG	3.96	3.80	2.64	2.49
days since last inpatient procedure	1.99	1.84	1.52	1.39
surgeon annual number of CABG procedures	98	100	126	129
years of experience	23.8	23.7	24.4	24.2
hospital annual number of CABG procedures	327	308	376	351
procedure characteristics (percent)				
1 vessel bypassed	30.68	26.94	29.58	25.60
2 vessels bypassed	35.22	34.83	34.31	34.27
3 vessels bypassed	25.07	27.23	26.00	28.02
4 or more vessels bypassed	9.02	10.99	10.11	12.11
cardiopulmonary bypass	63.19	57.51	65.07	61.09
concomitant valve procedure	21.21	17.10	21.66	17.72
emergent admission	29.65	100.00	29.74	100.00
urgent admission	23.52	0.00	22.21	0.00
elective admission	46.83	0.00	48.05	0.00
patient socio-demographic characteristics (percent)				
male	71.04	69.03	70.95	69.25
black	4.33	6.33	3.56	5.04
Hispanic	2.18	1.98	1.88	1.48
other race	6.12	6.10	5.96	5.02
patient age (years)	67.1	66.5	67.2	66.7
private insurance	34.22	33.62	33.80	33.78
Medicaid	5.53	7.79	5.11	7.13

Medicare	58.17	55.93	58.68	56.10
uninsured	2.09	2.66	2.41	2.98
patient clinical characteristics				
AMI* as admitting diagnosis	20.95	40.85	20.41	39.47
comorbid conditions (count)	1.38	1.32	1.36	1.29
congestive heart failure	11.22	14.10	10.53	13.21
valvular disease	6.14	5.69	6.13	5.65
pulmonary circulation disorders	1.42	1.13	1.26	1.11
peripheral vascular disorders	5.35	4.10	5.13	3.86
hypertension uncomplicated	35.36	28.57	35.77	29.04
hypertension complicated	5.52	6.52	5.37	6.20
paralysis	0.64	0.72	0.58	0.58
other neurological disorders	0.99	1.04	1.03	1.09
chronic pulmonary disease	11.81	11.80	12.10	12.28
diabetes-uncomplicated	15.24	13.72	15.14	13.01
diabetes-complicated	2.61	2.30	2.51	2.37
hypothyroidism	2.92	2.37	2.99	2.47
renal failure	6.42	7.28	6.51	7.24
liver disease	0.49	0.53	0.43	0.40
peptic ulcer disease-without bleed	0.01	0.01	0.00	0.01
AIDS	0.04	0.06	0.05	0.08
lymphoma	0.41	0.41	0.37	0.35
metastatic cancer	0.17	0.17	0.15	0.16
solid tumor	0.73	0.54	0.68	0.55
rheumatoid arthritis	0.65	0.62	0.66	0.68
coagulopathy	5.71	5.42	5.31	5.04
obesity	5.27	3.68	5.42	3.76
weight loss	1.44	1.90	1.30	1.64
fluid and electrolyte disorders	10.10	11.81	9.54	10.70
blood loss anemia	0.70	0.83	0.87	1.14
deficiency anemia	3.33	3.10	3.40	3.16
alcohol abuse	1.21	1.56	1.21	1.53
drug abuse	0.31	0.53	0.23	0.36
psychoses	0.56	0.81	0.48	0.72
depression	1.16	1.04	1.17	1.06

*Note: AMI is acute myocardial infarction.

Table 2. Patient Mortality

	1 day mortality		In-hospital mortality		1 day mortality		In-hospital mortality		1 day mortality		In-hospital mortality		1 day mortality		In-hospital mortality	
sample mean	0.62%		2.72%		0.89%		3.95%		0.52%		2.47%		0.71%		3.48%	
days since surgeon last performed CABG	0.010		0.032**		-0.001		0.038		0.033**		0.083***		0.076*		0.209***	
	(0.006)		(0.015)		(0.014)		(0.028)		(0.015)		(0.027)		(0.042)		(0.065)	
days since surgeon last performed any procedure		0.046***		0.067***		0.111***		0.202***		0.091***		0.168***		0.224***		0.398***
		(0.014)		(0.025)		(0.039)		(0.062)		(0.024)		(0.044)		(0.070)		(0.101)
ln(surgeon's annual CABG volume)	-0.227	-0.214	0.207	0.148	0.130	0.239	1.179	1.214*	0.120	0.128	1.185*	1.141*	1.316*	1.386*	2.930**	2.856**
	(0.206)	(0.210)	(0.374)	(0.363)	(0.397)	(0.398)	(0.725)	(0.708)	(0.291)	(0.289)	(0.606)	(0.599)	(0.752)	(0.757)	(1.261)	(1.206)
ln(hospital's annual CABG volume)	0.093	0.091	0.376	0.387	-0.544	-0.561	0.656	0.655	-0.100	-0.103	-0.049	-0.046	-0.953	-0.968	0.104	0.107
	(0.220)	(0.222)	(0.452)	(0.453)	(0.640)	(0.645)	(0.892)	(0.896)	(0.242)	(0.245)	(0.481)	(0.487)	(1.122)	(1.133)	(1.430)	(1.432)
Observations	56315	56315	56315	56315	16702	16702	16702	16702	33106	33106	33106	33106	9853	9853	9853	9853
Sample:																
Surgeon volume > 11 procedures	x	x	x	x												
Surgeon volume > 11 procedures-emergent cases					x	x	x	x								
Surgeon volume > 99 procedures									x	x	x	x				
Surgeon volume > 99 procedures-emergent cases													x	x	x	x

All coefficient estimates were multiplied by 100, and are thus percentage point effects

Standard errors clustered by surgeon in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All models include surgeon and hospital fixed effects and controls for patient race, payer, and comorbidity risk (Elixhauser et al, 1999)

Table 3. Total Charges (natural logarithm)

sample mean of costs	$35,343		$40,166		$32,900		$37,107	
days since surgeon last performed CABG	-0.103***		-0.113**		-0.430***		-0.404***	
	(0.032)		(0.051)		(0.065)		(0.126)	
days since surgeon last performed any procedure		-0.590***		-0.819***		-1.061***		-1.396***
		(0.074)		(0.131)		(0.129)		(0.225)
ln(surgeon's annual CABG volume)	-4.010**	-4.270**	-3.934*	-4.243**	-5.016	-4.995	-3.182	-3.823
	(1.760)	(1.771)	(2.037)	(2.038)	(3.299)	(3.134)	(3.367)	(3.377)
ln(hospital's annual CABG volume)	2.794*	2.833*	1.269	1.300	3.716**	3.736**	3.875	3.998
	(1.637)	(1.642)	(2.294)	(2.294)	(1.802)	(1.810)	(2.920)	(2.976)
Patient died in hospital	34.34***	34.40***	33.55***	33.79***	36.52***	36.67***	37.27***	37.64***
	(1.760)	(1.760)	(2.310)	(2.304)	(1.946)	(1.945)	(2.296)	(2.341)
Observations	56315	56315	16702	16702	33106	33106	9853	9853
Sample:								
Surgeon volume > 11 procedures	x	x						
Surgeon volume > 11 procedures-emergent cases			x	x				
Surgeon volume > 99 procedures					x	x		
Surgeon volume > 99 procedures-emergent cases							x	x

All coefficient estimates were multiplied by 100, and are thus percentage effects

Standard errors clustered by surgeon in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All models include surgeon and hospital fixed effects and controls for patient race, payer, and comorbidity risk (Elixhauser et al, 1999)

Table 4. Number of Comorbidities and Diagnosis of Acute Myocardial Infarction (AMI) at Admission

	Count of comorbidities				AMI as admitting diagnosis			
sample mean	1.38		1.36		21.0%		21.0%	
days since surgeon last performed CABG	-0.000		-0.000		0.033		0.097	
	(0.000)		(0.000)		(0.028)		(0.060)	
days since surgeon last performed any procedure		-0.000		0.000		0.048		0.102
		(0.000)		(0.000)		(0.065)		(0.090)
Observations	56315	56315	33106	33106	56315	56315	33106	33106
Surgeon Volume per Annum								
> 11	X	X			X	X		
> 99			X	X			X	X

AMI coefficient estimates were multiplied by 100, and are thus percentage effects
Standard errors clustered by surgeon in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All models include surgeon and hospital fixed effects and controls for patient race, payer, and comorbidity risk (Elixhauser et al, 1999)

Table 5. Cost per life-year saved

	All surgeons All admissions	All surgeons Emergent admissions	High-volume surgeons All admissions	High-volume surgeons Emergent admissions
Decrease in in-hospital mortality (percentage points)	0.067	0.202	0.168	0.398
Implied increase in life expectancy (years)[1]	0.012	0.036	0.029	0.070
Increase in costs ($)[2]	222	350	371	551
Cost per life-year saved ($)[3]	18,500	9,722	12,793	7,871

[1] Computed as decrease in in-hospital mortality times 17.6 years of post-CABG life expectancy divided by 100.

[2] Computed using the effect from temporal distance between any procedure and Duan's (1983) smearing estimator to retransform the log-transformed estimates.

[3] Computed as increase in costs divided by implied increase in life expectancy.