Health Information Technology and Mortality: Evidence from Hospital Hacker Attacks

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Abstract

The adoption of health information technology (IT) in medical practice was expected to revolutionize health care delivery and improve patient health outcomes. While there is evidence that health information technology increase healthcare quality for infants (Miller and Tucker, 2011), reduce mortality for complex patients (McCullough, Parente and Town, 2013), improves patient safety (Parente and McCullough, 2009) and has a modest effect on productivity (Lee, McCullough and Town, 2013) critics argue that realized benefits are small compared to projections and investment cost. A plausible explanation for the modest estimates of the effect of health IT on hospital production and patient outcomes is the inherent difficulty of identifying a causal path from technology adoption to hospital performance. Because the decision to adopt technology is not random, comparing hospitals that are early adopters of technology to those that adopt later may confound the adoption effect with other unobserved hospital characteristics that affect both the adoption decision and health outcomes.

In this paper, we use instances where individual hospitals' or hospital systems' information technology are compromised because of a cyberattack to quantify the importance of health information technology. A distinct advantage of this methodological approach is that we can look at within-hospital within-month variation in patient outcomes and hospital operations that happens after the hospital has already adopted the technology, and thus circumvent the problem of selection into technology adoption.

We collect data on cyberattacks aimed at hospitals from government reporting websites, local and national newspapers as well as third party websites that such report information. We distinguish between data breaches (loss of confidential data) and ransomware (complete takeover or disabling of computer systems) attacks. We merge information on cyberattacks with 2005 to 2018 detailed patient emergency department (ED) and inpatient data from California. Our main outcomes of interest are related to how disruptions in hospital IT affect hospital operations (ED visits and inpatient admissions) and patient outcomes (mortality, length of stay). We use differences-in-difference regression to compare outcomes at hospitals that experience a data breach or ransomware attack with similar hospitals that did not experience an attack. We also explore spillover effects of attacks on nearby hospitals.

We find that data breaches have no direct operational consequence on hospitals. Ransomware attacks on the other hand, which substantially hamper or completely shut down the hospital IT system and electronic health records, have an instant and significant effect on hospital operations and patient outcomes. We document an immediate decline in ED visits and inpatient admissions as a result of ransomware attacks. The operational disruptions caused by ransomware attacks are short-lived –lasting on average less than a week. However, we also uncover large positive impacts of ransomware attacks on inpatient mortality for those who are already hospitalized at the time of the attack, which strongly suggests that health IT disruptions translate into negative and substantial changes in the quality of care received. We also find evidence of spillover effects on nearby hospitals, which experience an increase in visits.

Introduction

Information technology has transformed work and everyday lives increasing the productivity of individuals and the business value of firms. In the healthcare sector, information technology has affected the provision of services in various ways. Health IT has enhanced patient care through the use of electronic health records and telehealth services, improved operational efficiency with the automation of tasks and easily accessible information and improved communication with secure communication platforms and interoperability. The reliance on in IT has increased the susceptibility of systems to cyber-attacks.

Hospitals and other healthcare facilities have been the targeted by various forms of malicious attacks. The majority of these breaches involve some loss of data confidentiality or IT system control. The type of attack we consider here – a ransomware attack – is an IT breach that allows the hacker to completely take over the hospital's IT system, and hold it hostage usually pending some sort of payment. This type of incident incapacitates the part of hospital operations that depend on electronic records, which these days includes everything from electronic pharmacy to claims administration, to patient health records from outpatient and inpatient encounters, potentially including the entire prior medical history of the patients.

These attacks involve the deployment of malicious software that encrypts critical data, rendering it inaccessible until a ransom is paid to the attackers. Hospitals and other healthcare facilities are increasingly being targeted due to their dependence on continuous access to sensitive patient information and the often inadequate cybersecurity measures in place to protect this data. This growing trend poses significant risks not only to the operational integrity of healthcare institutions but also to patient safety and overall health outcomes. Despite the alarming rate of increase of such attacks, we know little about their effects on hospital operations and, ultimately, patient outcomes. In this study, we investigate how hacker attacks, by incapacitating hospital IT operations and electronic health records, affected patient outcomes, and in particular patient in-hospital mortality.

The impact of ransomware on hospital operations can be devastating. In the immediate aftermath of an attack, hospitals often have to shut down affected systems to prevent the malware from spreading, which can lead to significant disruptions in day-to-day operations. Essential services such as surgery scheduling, patient admissions, and electronic prescribing can be severely hampered, forcing hospitals to revert to manual processes that are slower and more prone to errors. Such operational disruptions not only strain hospital resources but also delay patient care, potentially exacerbating medical conditions.

Patient outcomes could be directly and indirectly affected by the operational chaos caused by ransomware attacks. Delays in accessing vital patient records can lead to misdiagnoses, incorrect treatments, and postponed procedures. In critical care scenarios, even minor delays can have life-threatening consequences. Furthermore, the psychological impact on patients knowing their personal health information has been compromised can lead to increased anxiety and loss of trust in healthcare providers. This erosion of trust can lead to patients being reluctant to seek medical care, fearing their data may be at risk, which in turn can lead to worsening health outcomes over time.

We find immediate, and substantial effects of ransomware attacks on hospital operations. These manifest in fewer emergency department visits, and inpatient admissions. At the same time, we document large increases in in-hospital mortality for patients who were already hospitalized at the time of the attack, even after we control for patient health characteristics. Disrupting health IT infrastructure leads to large negative effects of patient outcomes.

Data

We use public information reported in newspaper articles, websites and government databases to collect information on cyber-attacks on hospitals in California. From these databases we get information on the dates and targets of different cyber-attacks – hacks, ransomware, and phishing.

Patient information comes from the four databases maintained by the California Department of Health Care Access and Information (HCAI). Information on patient characteristics such as admission and discharge dates, age, sex, race, disposition, health insurance type, diagnosis and procedures are from the Emergency Department and Inpatient databases.

We derive information on hospital characteristics such as number of beds, ownership status, net revenue, operating expenses, emergency room designation, rural and teaching status from Annual Financial data and Quarterly financial data

We use a sample of hospitals that experienced a cyber-attack in California. In our database, four hospitals experienced a phishing attack, ten experienced a hack and six hospitals experienced a ransomware attack[2].

Table 1: Summary Statistics

	Treatment Hospital			Control Hospitals		
	N	Mean	Std. Dev	N	Mean	Std. Dev
Average staffed beds	6	222.17	85.85	30	196.2	80.46
Percent Medicare	6	0.43	0.07	30	0.43	0.08
Percent Medicaid	6	0.32	0.15	30	0.33	0.12
Percent Private	6	0.22	0.11	30	0.19	0.12
Net Revenue ($1000s)	6	277,232	198,099	30	258,003	201,581
Total Operation Expense ($1000s)	6	271,258	200,861	30	256,943	208,384
For-Profit	6	0.67	0.52	30	0.67	0.48
Not-for-Profit	6	0.33	0.52	30	0.33	0.48

Sample

For each hospital, we run a nearest neighbor matching algorithm to find comparison hospitals using characteristics from year before the attack. Candidate comparison hospitals must be outside the health service area (HSA) of the attacked hospital. We consider hospitals outside the HSA of

[2] We present a list of hospitals that experience these attacks in Appendix Table 1.

the attacked hospital because disruptions at an attacked hospital can spillover to nearby hospitals. Using hospitals outside the HSA minimizes the potential of choosing a hospital that experiences a residual impact of the attack. We match hospitals using the following variables: average staffed beds, log of net revenue, log of total operating income, log total operating expense, percent of discharges paid with Medicare, Medicaid, and private insurance. We also include dummy variables for ER designation and teaching and rural status. For each hospital, we chose the top five matched hospitals as comparison.

Empirical Methodology

To analyze the impact of ransomware attacks on hospital operations we aggregate patient data for each day of the week up seven days before and after an attack. Our identification compares outcomes for attacked and comparison hospitals seven days before and after an attacked. We estimate the following equation:

$$Y_{ht} = \alpha + \beta * Post_{ht} + \gamma * Treat_{ht} + \theta * (Post * Treat)_{ht} + \zeta_t + \kappa_h + \varepsilon_{ht}$$

The dependent variable Y_{ht} measures the following variables: total number of visits, number of visits by patients less than 65 years old, number of visits by patients older than 65 years old, total visits by type of insurance (Medicare, Medicaid, private and self-pay). We also consider visits by sex and by race. Our final measures of hospital operations are the total number of diagnosis and total procedures for each day to capture potential changes in case mix. The variable $Post_{ht}$ is 1 for days before the attack and 0 for days after the attack. $Treat_{ht}$ is equal to 1 for hospitals that experienced an attack and 0 for comparison hospitals. The interaction of Post and Treat measures the impact of an attack by comparing outcomes for attacked hospital to comparison hospitals before and after the cyber-attack incident.

Ransomware attack may change hospital operations as hospitals may alter their standard operating procedures to counter the lose of their health information technology. This means that identifying the effect of attacks on patient outcomes using a DID framework that compares outcomes before and after an attack will lead to biased results. We use a different estimating equation to identify potential changes in patient outcomes induced by a cyber-attack.

We first start with the following identifying equation:

$$Y_{iht} = \alpha + \beta * Exposed_{iht} + \gamma * Treat_{iht} + \theta * Exposed * Treat_{iht} + \psi * X_{iht} + \zeta_t + \kappa_h + \varepsilon_{iht}$$

This equation is similar to equation X with a few exceptions. The level of analysis here is at the individual hospital time level. The variable *Exposed* is equal to one for individuals who are admitted to a hospital up to one week before an attack and discharged after an attack. The coefficient θ on the interaction term $Exposed * Treat_{iht}$ measures the differential effect of a cyber-attack on patients admitted to an attacked hospital. We also include a vector of patient characteristics, X_{iht}. The characteristics included in our regression are: age, age-squared, sex, race, insurance type (Medicare, Medicaid, private, self-pay), Charlson comorbidity index, and type of care (acute, skilled nursing, psychiatric care, chemical dependency recovery care or physical rehabilitation care). Equation X identifies the impact of ransomware attacks on patient outcomes, but may not completely account for seasonal trends that may differ by hospital.

Our preferred specification, uses prior five years of data for the same week of the year and day of the week as the attack date for attacked and comparison hospitals to compare patient outcomes for patients admitted to a hospital up to seven days before the attack date. Using prior data allows us to purge any contemporaneous seasonal hospital-specific trends that may differ between attacked and comparison hospitals. To evaluate the impact of an attack on patient outcomes, we estimate the following equation:

$$Y_{iht} = \alpha + \beta * Exposed_{iht} + \gamma * Treat_{iht} + Attack\ Year + \theta * (Exposed * Treat)_{iht} + \eta * (Exposed * Attack\ Year)_{iht} + \varphi * (Treat * Attack\ Year)_{iht} + \boldsymbol{\omega} * (\boldsymbol{Exposed * Treat * Attack\ Year})_{\boldsymbol{iht}} + \psi * X_{iht} + \zeta_t + \kappa_h + \varepsilon_{iht}$$

In the above equation we isolate the year of attack to compare outcomes for that year to other years prior to that attack. The variable $Attack\ Year$ is equal to 1 for the year of attack and 0 otherwise, $Exposed * Attack\ Year_{iht}$ measures the difference in outcomes for *Exposed* patients (patients admitted before an attack and discharged on or after the date of an attack) in the year of attack compared to years prior to the attack.

Results

Table 2: Effect of Ransomware on the Composition of Hospital Emergency Department Visits

	Total Visits	Total Visits-over 65	Total Visits-under 65	Medicare	Medicaid	Private	Self Pay
after x treat	-10.117***	-0.563	-9.554***	-1.931**	-3.965*	-3.703	0.075
	(3.244)	(0.814)	(2.995)	(0.747)	(2.021)	(3.087)	(0.791)
Constant	115.734***	17.184***	98.550***	19.955***	50.190***	33.183***	9.672***
	(2.100)	(1.080)	-2.045	(1.379)	(1.558)	(0.936)	(0.746)
Pre-treatment mean	106.31	15.4	90.91	16.77	36.2	40.97	9.8
Day of week fixed effects	Y	Y	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y	Y	Y
Observations	450	450	450	450	450	450	450
R-squared	0.969	0.929	0.960	0.939	0.949	0.948	0.750

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 3: Effect of Ransomware on the Composition of Hospital Emergency Department Visits

	Number of Diagnosis	Number of Procedures	Male	Female	White	Black
after x treat	-0.304**	-0.162	-6.717***	-3.411	-2.621	-2.281**
	(0.142)	(0.177)	(1.525)	(3.119)	(1.748)	(0.881)
Constant	3.143***	2.902***	51.186***	64.555***	42.721***	12.709***
	(0.101)	(0.094)	(1.183)	(1.672)	(1.420)	(0.703)
Pre-treatment mean	2.68	4.32	47.66	58.66	33.03	12.94
Day of week fixed effects	Y	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y	Y
Observations	450	450	450	450	450	450
R-squared	0.907	0.975	0.931	0.949	0.970	0.974

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 4: Effect of Ransomware on Direct Inpatient Admissions

	Total Visits	Total Visits-over 65	Total Visits-under 65	Medicare	Medicaid	Private	Self-Pay
after x treat	1.654	1.106	0.548	1.659	0.304	0.058	-0.131
	(1.787)	(1.266)	(1.032)	(1.213)	(1.016)	(0.672)	(0.207)
Constant	24.803***	6.263***	18.540***	6.569***	7.302***	9.730***	0.708***
	(1.578)	(0.556)	(1.151)	(0.569)	(0.397)	(0.769)	(0.256)
Pre-treatment mean	29.03	10.08	18.94	10.28	7.36	9.94	0.53
Day of week fixed effects	Y	Y	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y	Y	Y
Observations	513	513	513	513	513	513	513
R-squared	0.935	0.910	0.914	0.909	0.746	0.924	0.694

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 5: Effect of Ransomware on Direct Inpatient Admissions

	Number of Diagnosis	Charges	Black	White
after x treat	0.440	-11,603.362	0.254*	-0.710
	(0.489)	(8,181.782)	(0.146)	(1.020)
Constant	8.393***	65,757.252***	1.575***	13.472***
	(0.284)	(3,504.742)	(0.170)	(1.088)
Pre-treatment mean	7.58	76,675	2.19	14.53
Day of week fixed effects	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y
Observations	513	468	513	513
R-squared	0.608	0.693	0.713	0.928

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 6: Effect of Ransomware on Inpatient Admissions through the Emergency Department

	Total Visits	Total Visits-over 65	Total Visits-under 65	Medicare	Medicaid	Private	Self-Pay
after x treat	-4.903***	-2.310***	-2.593**	-1.148	-2.606**	-1.080**	0.083
	(1.491)	(0.605)	(1.193)	(0.676)	(1.096)	(0.492)	(0.085)
Constant	17.248***	8.713***	8.535***	9.063***	5.170***	2.340***	0.438***
	(0.794)	(0.598)	(0.463)	(0.461)	(0.569)	(0.184)	(0.131)
Pre-treatment mean	20.11	9.07	11.04	8.86	7.64	3.11	0.14
Day of week fixed effects	Y	Y	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y	Y	Y
Observations	399	399	399	399	399	399	399
R-squared	0.876	0.774	0.815	0.762	0.772	0.861	0.355

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 7: Effect of Ransomware on Inpatient Admissions through the Emergency Department

	Number of Diagnosis	LOS	Black	White	Charges
after x treat	-0.960**	-0.480	-0.812	-2.291***	-17,050.196***
	(0.384)	(0.344)	(0.568)	(0.607)	(5,811.402)
Constant	13.417***	5.015***	2.436***	9.606***	107,469.279***
	(0.255)	(0.356)	(0.269)	(0.510)	(5,855.243)
Pre-treatment mean	12.54	4.74	2.68	11.25	74,812
Day of week fixed effects	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y
Observations	399	399	399	399	354
R-squared	0.684	0.331	0.917	0.784	0.650

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 8: Spillover Effect of Ransomware Attack Hospital Emergency Department Visits and by Payer Type

	Total Visits	Total Visits-over 65	Total Visits-under 65	Medicare	Medicaid	Private	Self-Pay
after x treat	2.194**	-0.266	2.460***	-0.310	1.860***	0.059	0.668***
	(0.948)	(0.276)	(0.851)	(0.274)	(0.607)	(0.431)	(0.256)
Constant	130.548***	20.192***	110.356***	23.842***	58.496***	35.035***	9.684***
	(0.892)	(0.239)	(0.823)	(0.256)	(0.619)	(0.359)	(0.219)
Pre-treatment mean	119.04	16.3	102.73	18.63	54.33	32.34	10.66
Day of week fixed effects	Y	Y	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y	Y	Y
Observations	12,045	12,045	12,045	12,045	12,045	12,045	12,045
R-squared	0.957	0.907	0.949	0.905	0.948	0.953	0.733

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 9: Spillover Effect of Ransomware on the Composition of Hospital Emergency Department Visits

	Number of Diagnosis	Number of Procedures	Male	Female	White	Black
after x treat	-0.034	-0.029	0.661	1.534**	-0.217	0.143
	(0.028)	(0.023)	(0.526)	(0.616)	(0.469)	(0.311)
Constant	3.342***	3.075***	58.523***	72.021***	50.352***	14.340***
	(0.024)	(0.039)	(0.418)	(0.680)	(0.421)	(0.246)
Pre-treatment mean	3.07	2.86	54.71		64.32	18.98
Day of week fixed effects	Y	Y	Y	Y	Y	Y
Month fixed effects	Y	Y	Y	Y	Y	Y
Day of month fixed effects	Y	Y	Y	Y	Y	Y
Facility fixed effects	Y	Y	Y	Y	Y	Y
Observations	12,045	12,045	12,045	12,045	12,045	12,045
R-squared	0.833	0.940	0.928	0.937	0.957	0.940

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 10: Effect of Ransomware Attack on Patient Outcomes—All Patients

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.056***	-0.004	-0.019***	-0.016**
	(0.017)	(0.009)	(0.006)	(0.008)
exposed x treat	0.024	0.029***	-0.004	-0.003
	(0.031)	(0.010)	(0.007)	(0.011)
Constant	0.148**	0.063**	0.038***	0.010
	(0.061)	(0.030)	(0.012)	(0.013)
Observations	5,805	6,576	6,576	6,576
R-squared	0.090	0.051	0.028	0.084

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 11: Effect of Ransomware Attack on Patient Outcomes--Medicare

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.049**	-0.004	-0.021	-0.012
	(0.021)	(0.011)	(0.013)	(0.009)
exposed x treat	0.025	0.051**	-0.020	-0.015
	(0.050)	(0.020)	(0.018)	(0.015)
Constant	0.174	0.132**	-0.071**	0.132**
	(0.146)	(0.052)	(0.034)	(0.064)
Observations	2,906	2,958	2,958	2,958
R-squared	0.083	0.057	0.053	0.269

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 12: Effect of Ransomware Attack on Patient Outcomes-Over 65

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.044*	0.005	-0.024*	-0.006
	(0.026)	(0.010)	(0.013)	(0.010)
exposed x treat	0.028	0.045**	-0.009	-0.029*
	(0.046)	(0.018)	(0.016)	(0.015)
Constant	0.267	0.433	0.067	0.104
	(0.608)	(0.286)	(0.284)	(0.145)
Observations	2,643	2,733	2,733	2,733
R-squared	0.079	0.058	0.051	0.287

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 13: Effect of Ransomware Attack on Patient Outcomes--Under 65

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.067***	-0.011	-0.018**	-0.027***
	(0.023)	(0.012)	(0.008)	(0.008)
exposed x treat	0.029	0.017*	0.001	0.020*
	(0.038)	(0.009)	(0.012)	(0.012)
Constant	0.096	0.046	0.039***	0.012
	(0.075)	(0.027)	(0.014)	(0.015)
Observations	3,160	3,841	3,841	3,841
R-squared	0.119	0.063	0.043	0.057

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 14: Effect of Ransomware Attack on Patient Outcomes-Private

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.033	-0.024***	-0.002	-0.017*
	(0.031)	(0.008)	(0.012)	(0.009)
exposed x treat	0.068**	0.031***	0.018	0.008
	(0.028)	(0.007)	(0.022)	(0.013)
Constant	0.186**	0.042***	0.029**	0.014***
	(0.084)	(0.012)	(0.012)	(0.005)
Observations	1,205	1,408	1,408	1,408
R-squared	0.134	0.182	0.081	0.055

Appendix Tables

Table A1: Effect of Ransomware Attack on Patient Outcomes-All Patients; triple difference

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.080***	0.001	-0.008***	0.055***
	(0.006)	(0.002)	(0.002)	(0.009)
attack year	0.012	0.007*	0.001	0.029***
	(0.010)	(0.004)	(0.005)	(0.006)
exposed x treat	0.031	0.004	-0.000	-0.021
	(0.019)	(0.003)	(0.003)	(0.013)
treat x attack year	-0.024	-0.010**	-0.002	0.004
	(0.021)	(0.005)	(0.007)	(0.009)
exposed x attack year	-0.022*	-0.003	-0.009	-0.051***
	(0.011)	(0.005)	(0.005)	(0.011)
exposed x treat x attack year	-0.015	0.025***	-0.008	0.018
	(0.035)	(0.009)	(0.007)	(0.020)
Constant	-0.017	0.015***	0.027***	-0.068***
	(0.025)	(0.005)	(0.010)	(0.016)
Observations	34,904	39,517	39,517	39,517
R-squared	0.058	0.037	0.042	0.110

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A2: Effect of Ransomware Attack on Patient Outcomes-Over 65; triple difference

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.082***	0.003	-0.012***	0.091***
	(0.008)	(0.004)	(0.004)	(0.012)
attack year	0.015	0.007	-0.000	0.043***
	(0.016)	(0.006)	(0.008)	(0.013)
exposed x treat	0.035	0.007	-0.000	-0.022
	(0.023)	(0.005)	(0.007)	(0.022)
treat x attack year	-0.029	-0.010	-0.000	0.028
	(0.031)	(0.009)	(0.017)	(0.018)
exposed x attack year	-0.033*	0.001	-0.010	-0.069***
	(0.019)	(0.006)	(0.010)	(0.017)
exposed x treat x attack year	-0.013	0.038**	-0.019	-0.000
	(0.038)	(0.016)	(0.016)	(0.029)
Constant	-0.097	0.205*	-0.006	0.279
	(0.291)	(0.106)	(0.093)	(0.218)
Observations	16,014	16,452	16,452	16,452
R-squared	0.035	0.040	0.065	0.164

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A3: Effect of Ransomware Attack on Patient Outcomes-Medicare; triple difference

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.085***	0.002	-0.010***	0.087***
	(0.010)	(0.003)	(0.003)	(0.013)
attack year	0.006	0.012	-0.001	0.046***
	(0.014)	(0.008)	(0.008)	(0.013)
exposed x treat	0.033	0.008	-0.002	-0.018
	(0.029)	(0.005)	(0.007)	(0.022)
treat x attack year	-0.023	-0.007	0.008	0.011
	(0.033)	(0.009)	(0.020)	(0.020)
exposed x attack year	-0.025	-0.006	-0.008	-0.068***
	(0.018)	(0.007)	(0.011)	(0.018)
exposed x treat x attack year	-0.013	0.035**	-0.025	0.008
	(0.039)	(0.015)	(0.016)	(0.029)
Constant	0.273***	0.041***	-0.045**	0.070
	(0.064)	(0.015)	(0.019)	(0.049)
Observations	17,088	17,337	17,337	17,337
R-squared	0.035	0.037	0.048	0.155

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A4: Effect of Ransomware Attack on Patient Outcomes-Under 65; triple difference

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.075***	-0.001	-0.006***	0.016**
	(0.009)	(0.002)	(0.002)	(0.007)
attack year	0.007	0.007*	0.002	0.012***
	(0.014)	(0.004)	(0.006)	(0.004)
exposed x treat	0.015	0.003	-0.002	-0.017**
	(0.014)	(0.003)	(0.002)	(0.008)
treat x attack year	-0.020	-0.011**	-0.001	-0.011
	(0.026)	(0.004)	(0.010)	(0.008)
exposed x attack year	-0.010	-0.006	-0.007	-0.031***
	(0.014)	(0.007)	(0.007)	(0.007)
exposed x treat x attack year	-0.001	0.013	0.001	0.036**
	(0.043)	(0.010)	(0.011)	(0.016)
Constant	0.015	0.009**	0.025***	-0.018
	(0.027)	(0.003)	(0.007)	(0.011)
Observations	18,890	23,065	23,065	23,065
R-squared	0.083	0.043	0.029	0.054

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table A5: Effect of Ransomware Attack on Patient Outcomes-Private: triple difference

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.061***	-0.006	-0.005*	0.011*
	(0.013)	(0.004)	(0.003)	(0.006)
attack year	0.013	0.004	-0.005	0.003
	(0.018)	(0.006)	(0.006)	(0.006)
exposed x treat	0.028	0.004	0.003	-0.012
	(0.018)	(0.003)	(0.004)	(0.010)
treat x attack year	-0.016	-0.010	0.003	-0.012
	(0.027)	(0.008)	(0.006)	(0.009)
exposed x attack year	0.004	-0.016***	-0.004	-0.021***
	(0.020)	(0.005)	(0.006)	(0.005)
exposed x treat x attack year	0.030	0.027***	0.007	0.026
	(0.033)	(0.007)	(0.017)	(0.020)
Constant	0.050	0.013***	0.021***	0.006
	(0.032)	(0.004)	(0.005)	(0.005)
Observations	7,899	9,207	9,207	9,207
R-squared	0.063	0.084	0.033	0.058

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

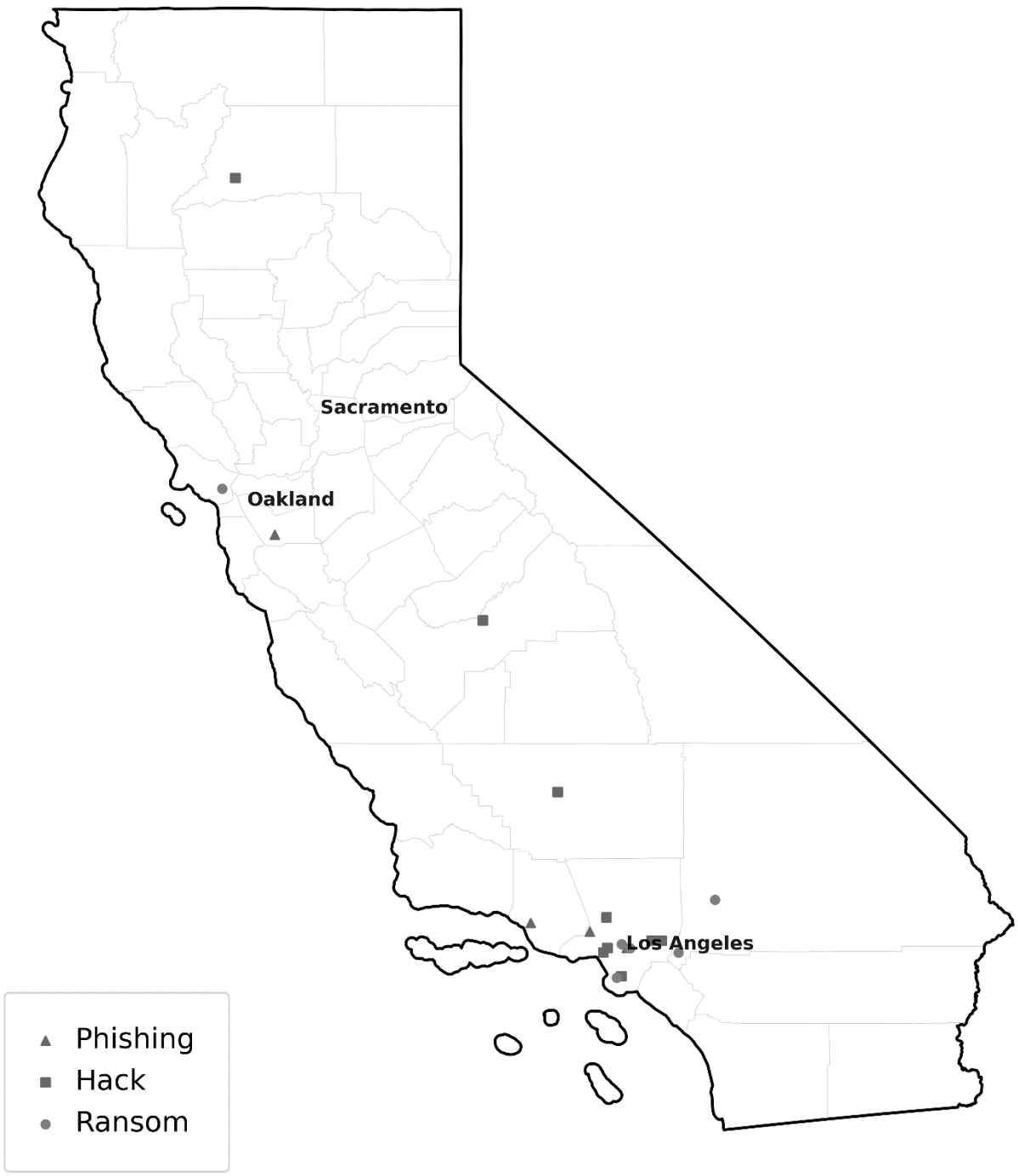
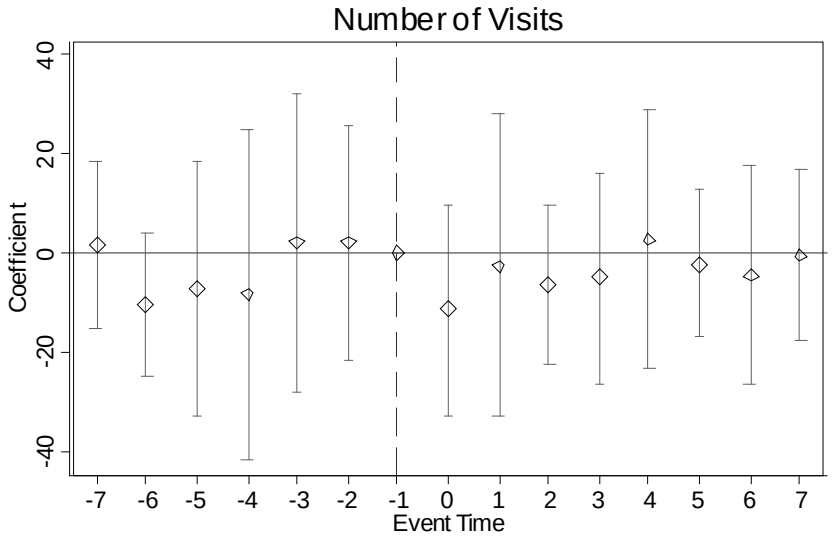
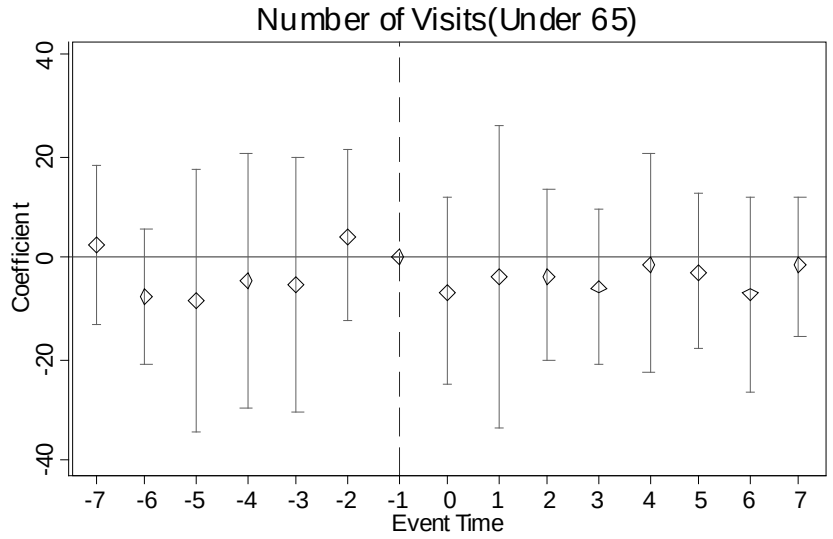
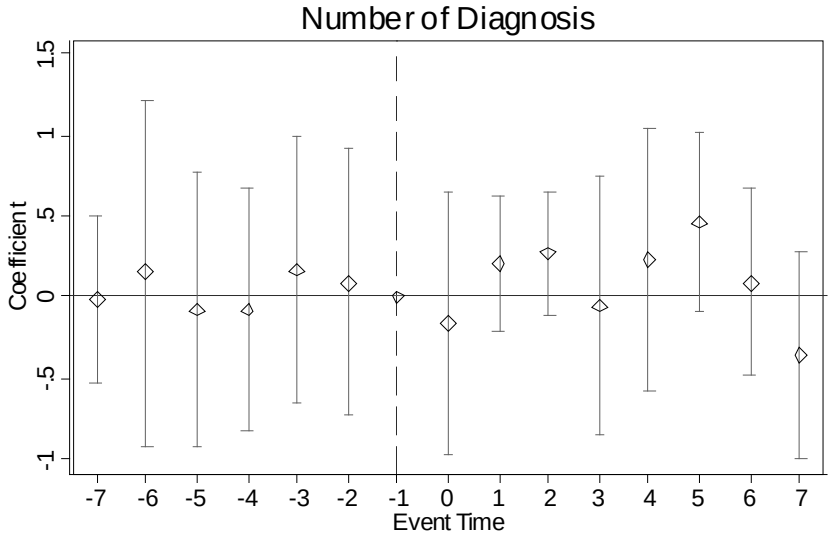


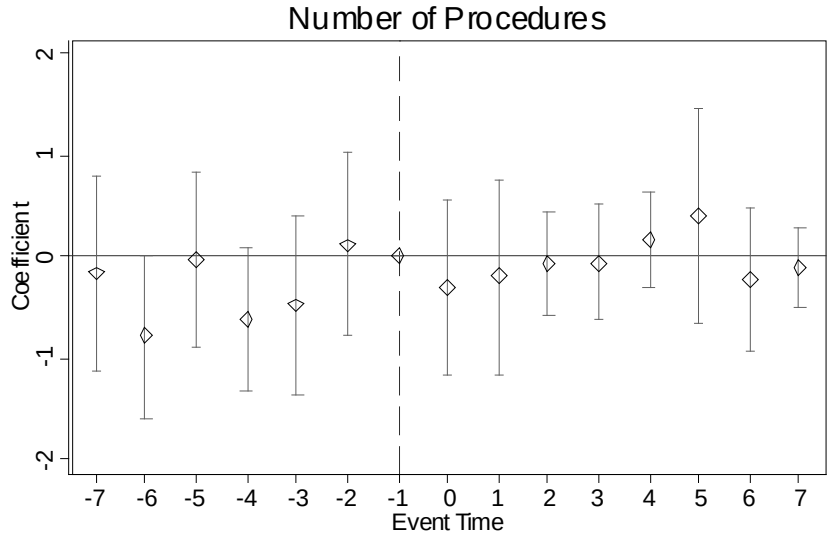
Figure 1: Location of California Hospital Cyberattacks

Effect of phishing attack on emergency visits

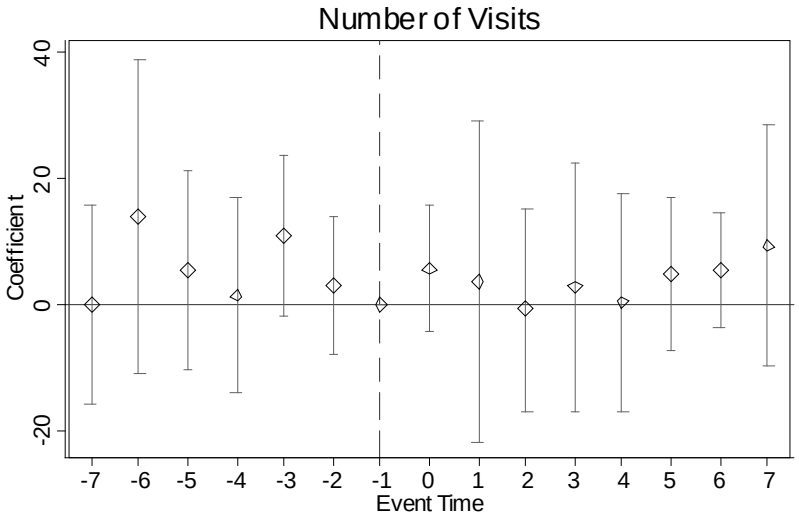


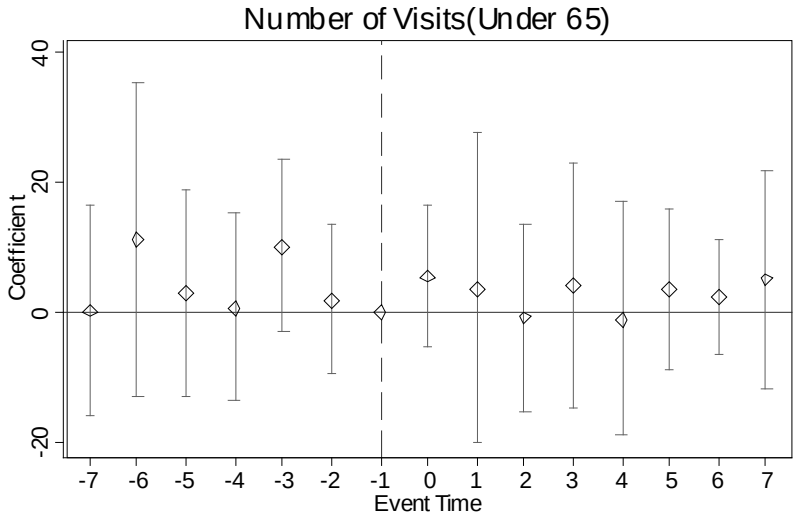


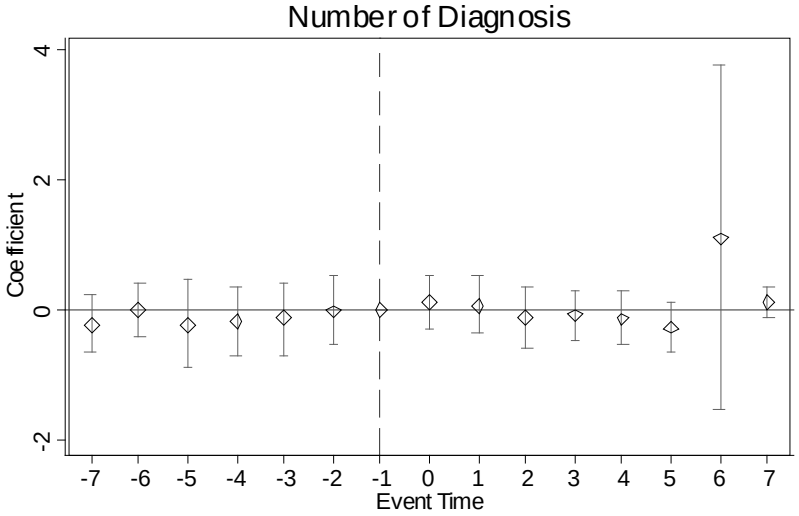


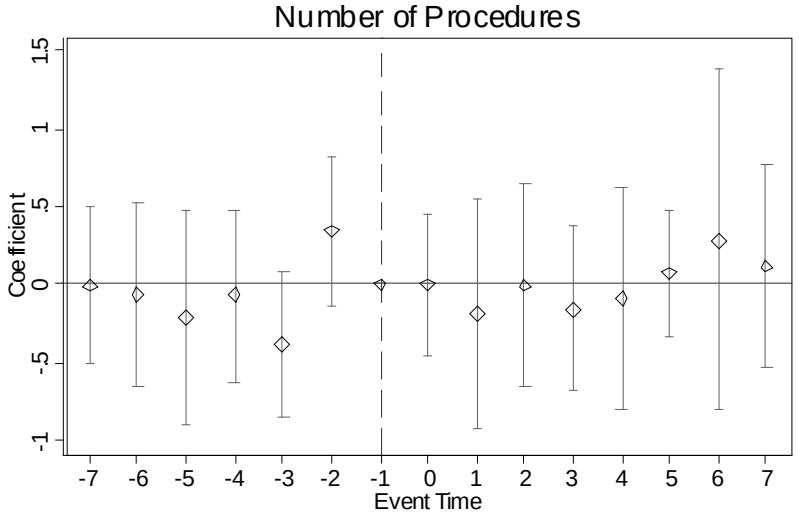


Effect of hack attack on emergency visits

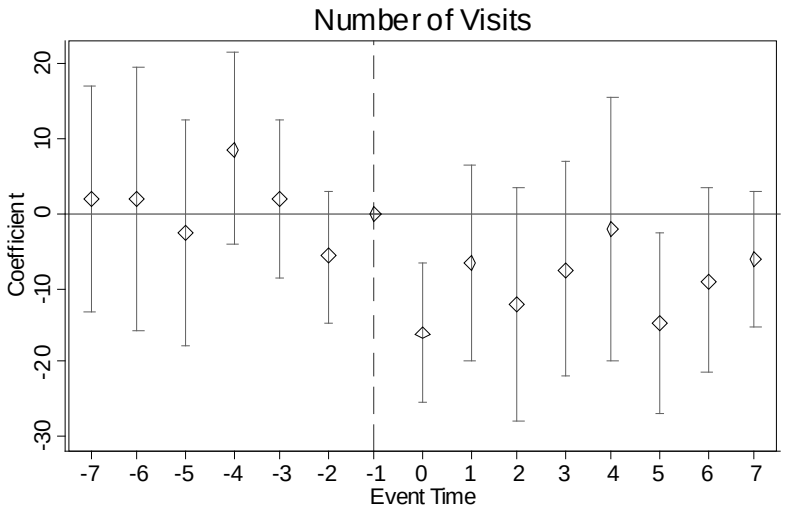


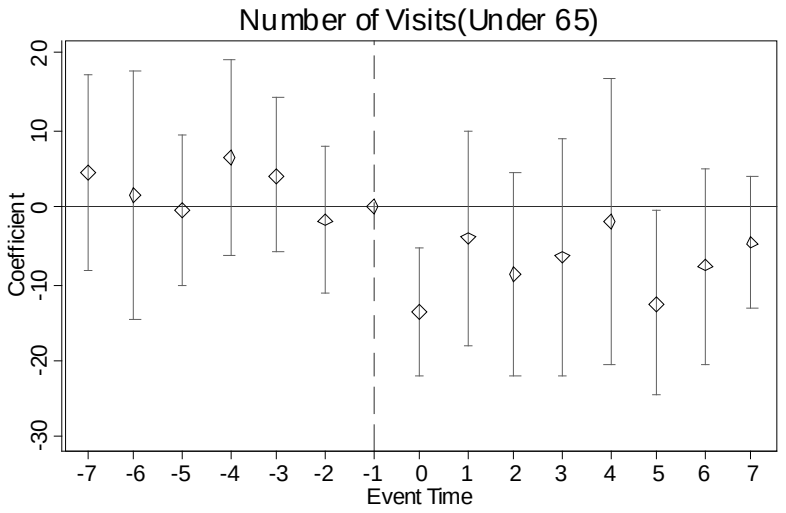


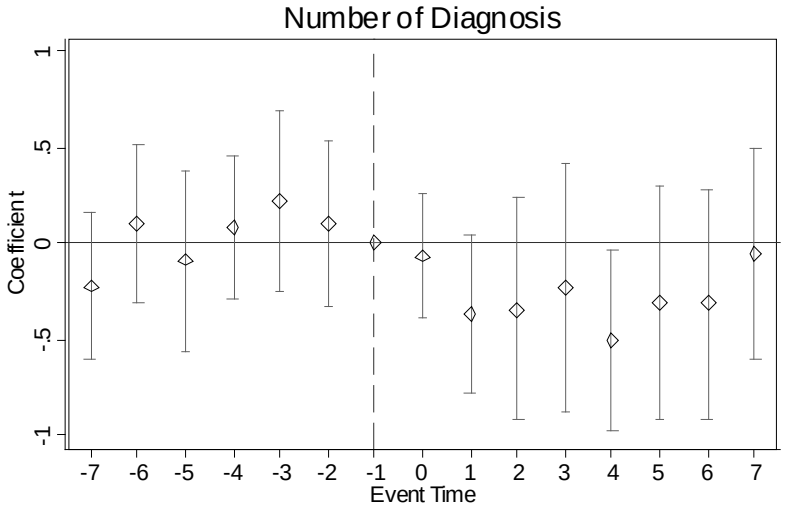


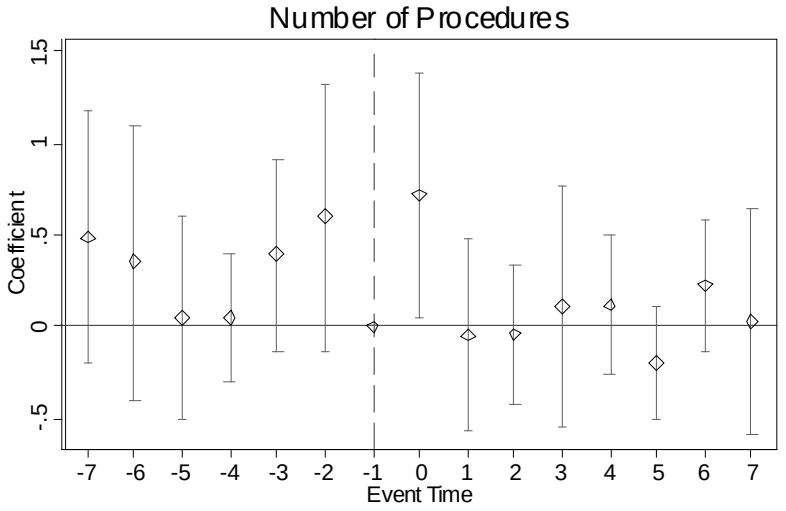


Effect of ransom attack on emergency visits

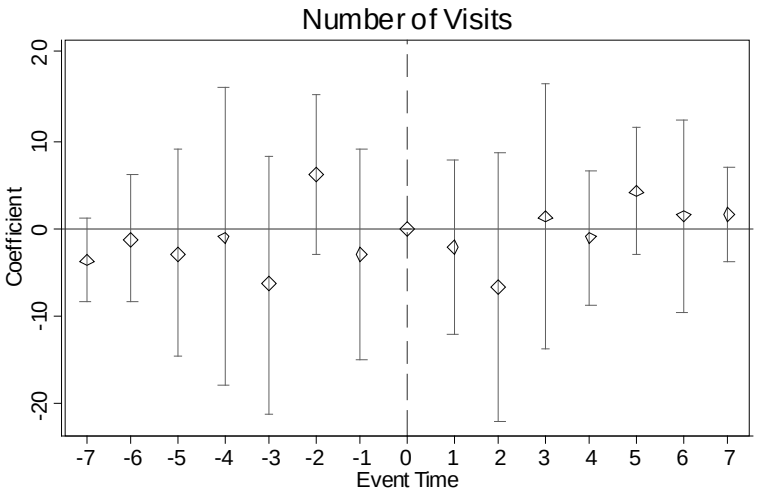


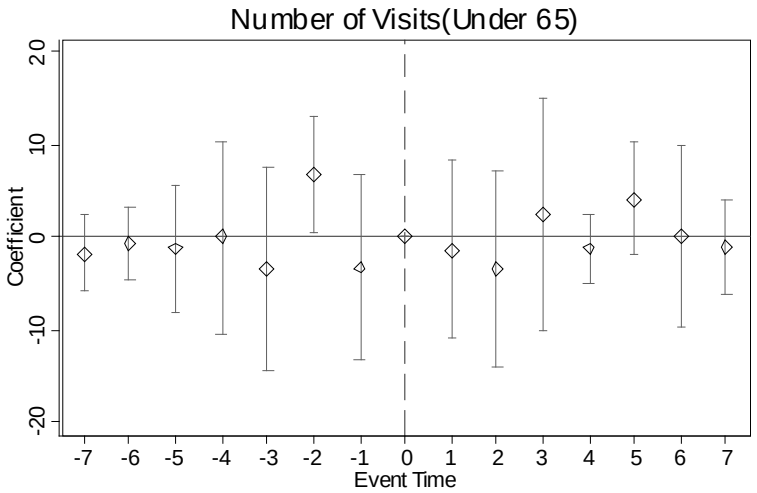


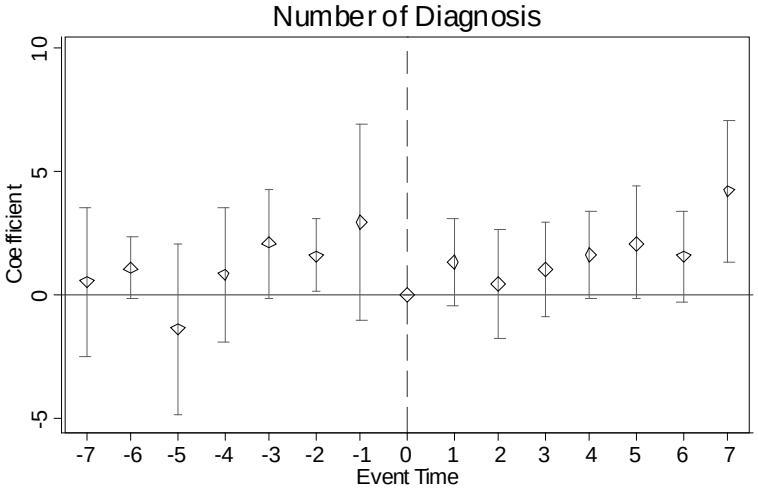


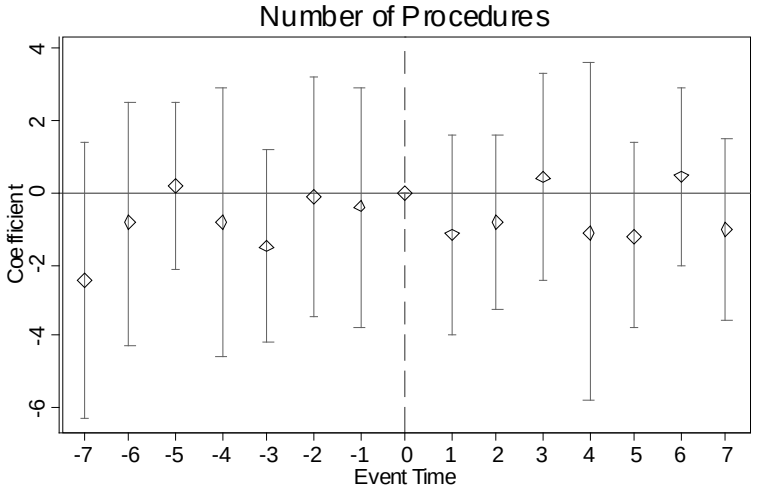


Effect of ransom attack on direct inpatient admissions

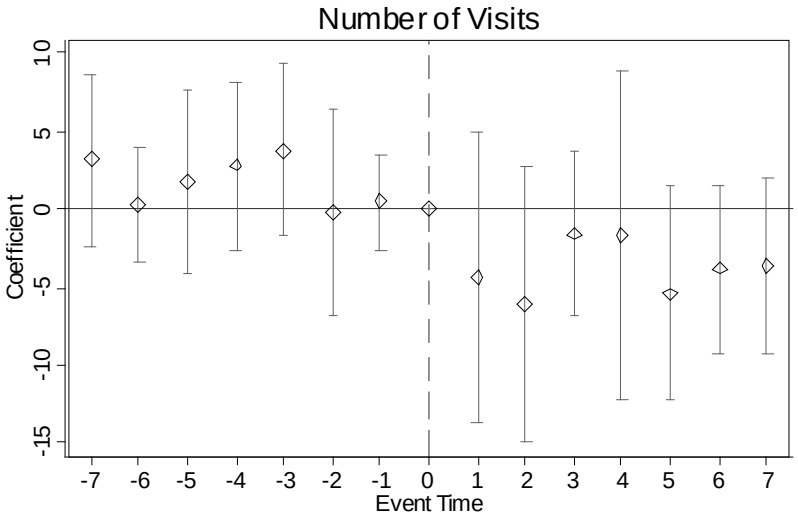


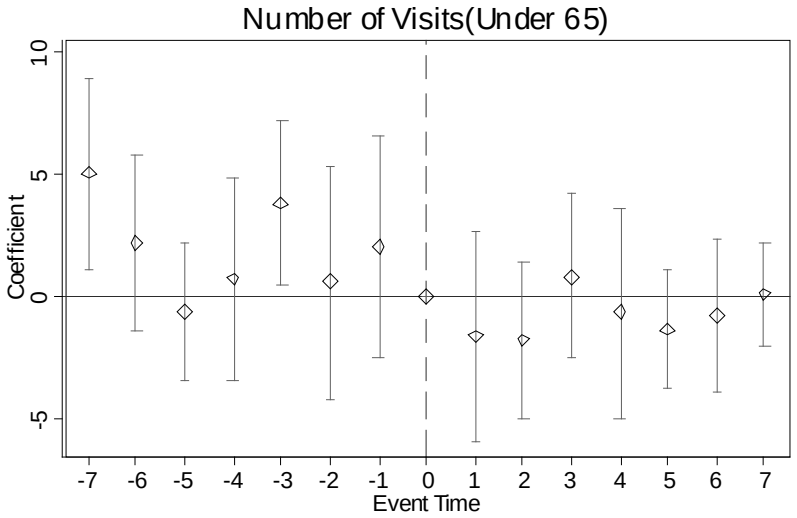


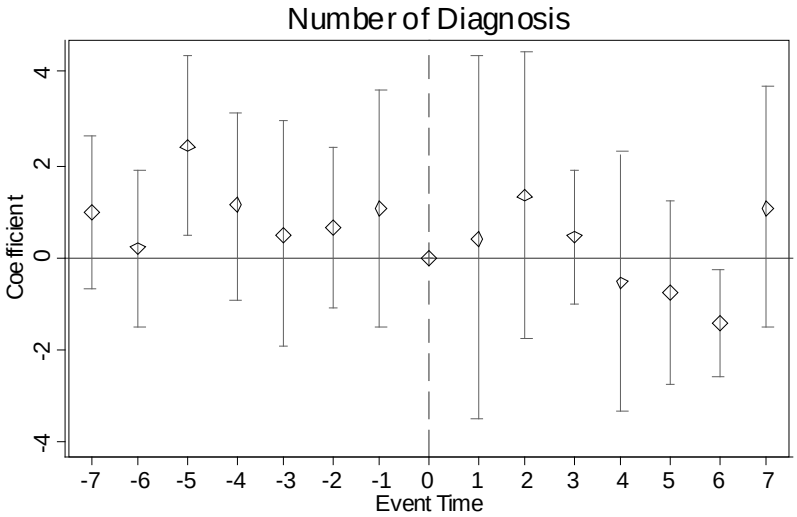


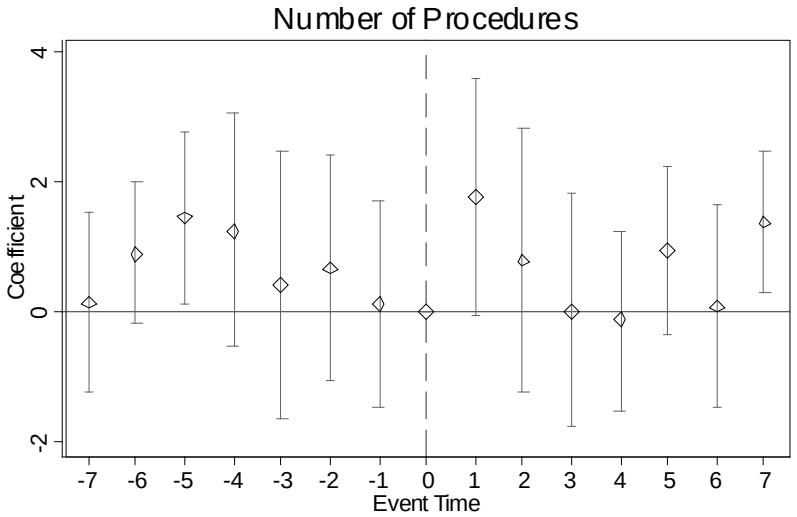


Effect of ransom attack on ED inpatient admissions

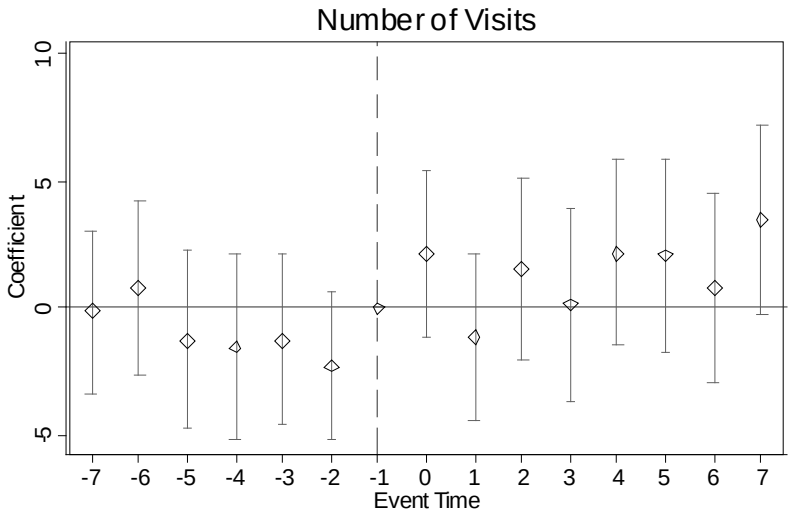


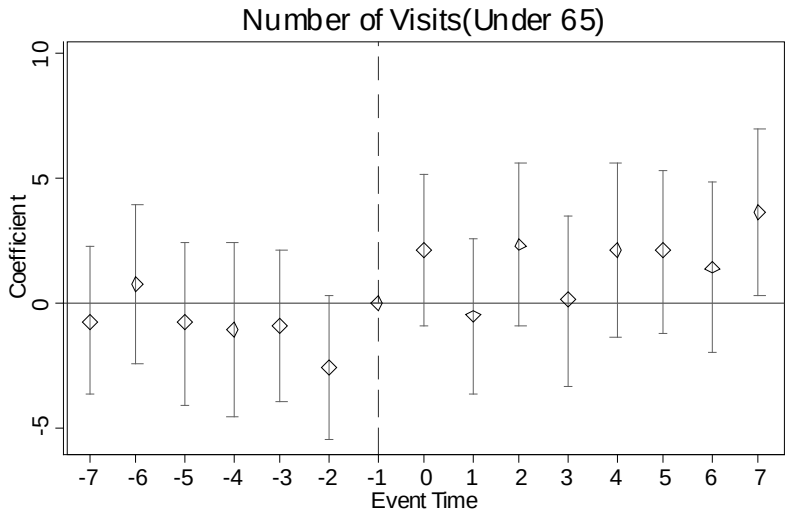


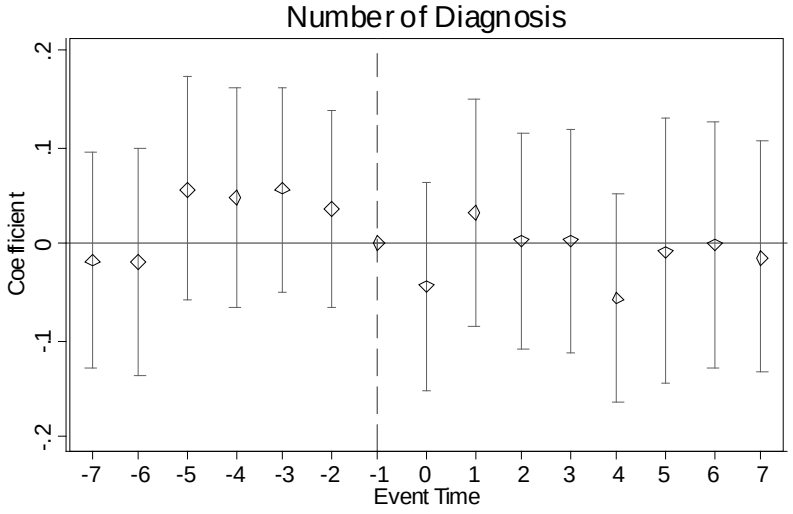


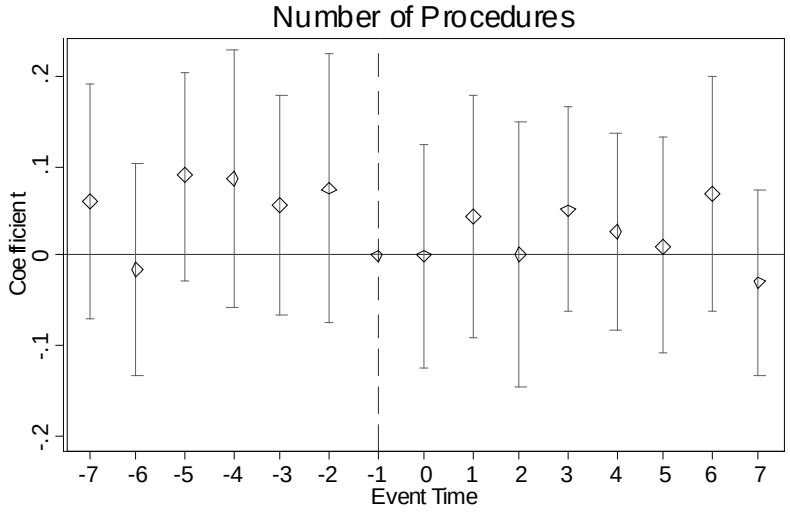


Spillover Effect of ransom attack on Emergency Visits









Appendix Table 1

List of Hospitals by Breach Type and Date

Facility Name	City	Breach Type	Attack Date
UCLA Neuropsychiatric Hospital	Los Angeles	Hack	9/1/2014
UCLA Medical Center-LAC/Olive View	Sylmar	Hack	9/1/2014
UCLA Medical Center-Santa Monica	Santa Monica	Hack	9/1/2014
UCLA Medical Center-LAC/Harbor	Torrance	Hack	9/1/2014
UCLA Medical Center	Los Angeles	Hack	9/1/2014
St. Agnes Medical Center	Fresno	Hack	1/1/2015
Mercy Medical Center	Redding	Hack	4/5/2015
Washington Hospital - Fremont	Fremont	Phishing	2/3/2016
Hollywood Presbyterian Medical Center	Los Angeles	Ransomware	2/5/2016
Chino Valley Medical Center	Chino	Ransomware	3/18/2016
Desert Valley Hospital	Victorville	Ransomware	3/18/2016
Marin General Hospital	San Rafael	Ransomware	7/26/2016
East Valley Hospital Med Center	Glendora	Hack	7/27/2016
USC University Hospital	Los Angeles	Ransomware	8/1/2016
Pacific Alliance Medical Center	Los Angeles	Phishing	5/15/2017
City Of Hope National Medical Center	Duarte	Hack	5/27/2017
Community Mem Hospital-San Buenaventura	Ventura	Phishing	5/31/2017
Torrance Memorial Medical Center	Torrance	Ransomware	6/14/2017
Kern Medical Center	Bakersfield	Hack	12/8/2017
West Hills Hospital and Medical Center	West Hills	Phishing	11/1/2018

APPENDIX

Table X: Effect of Ransomware Attack on Patient Outcomes-All Patients

	30-day Readmission	In-hospital Mortality	Transfer	Left Against Medical Advice
exposed	0.080***	0.001	-0.008***	0.055***
	(0.006)	(0.002)	(0.002)	(0.009)
attack year	0.012	0.007*	0.001	0.029***
	(0.010)	(0.004)	(0.005)	(0.006)
exposed x treat	0.031	0.004	-0.000	-0.021
	(0.019)	(0.003)	(0.003)	(0.013)
treat x attack year	-0.024	-0.010**	-0.002	0.004
	(0.021)	(0.005)	(0.007)	(0.009)
exposed x attack year	-0.022*	-0.003	-0.009	-0.051***
	(0.011)	(0.005)	(0.005)	(0.011)
exposed x treat x attack year	-0.015	0.025***	-0.008	0.018
	(0.035)	(0.009)	(0.007)	(0.020)
Constant	-0.017	0.015***	0.027***	-0.068***
	(0.025)	(0.005)	(0.010)	(0.016)
Observations	34,904	39,517	39,517	39,517
R-squared	0.058	0.037	0.042	0.110

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1