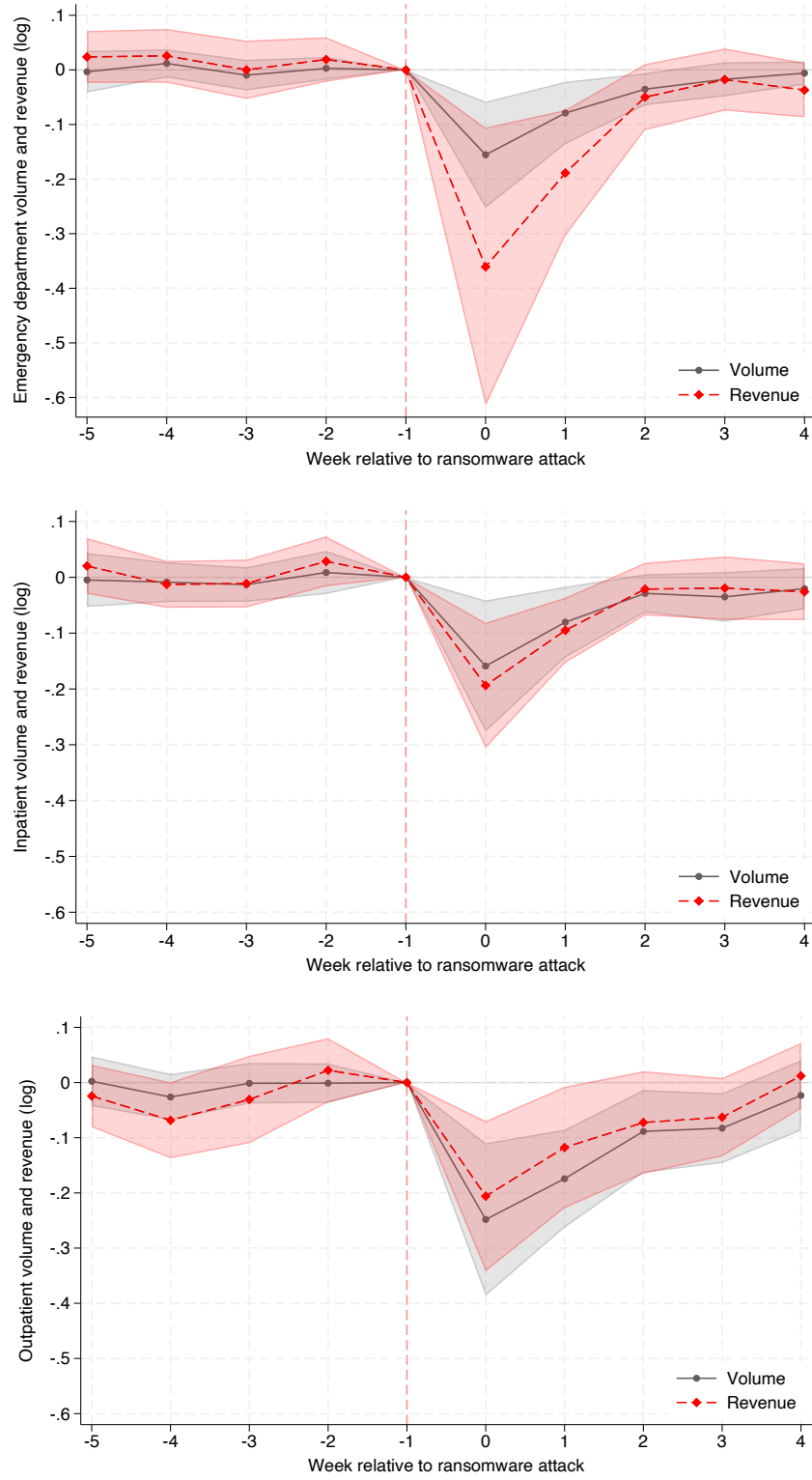


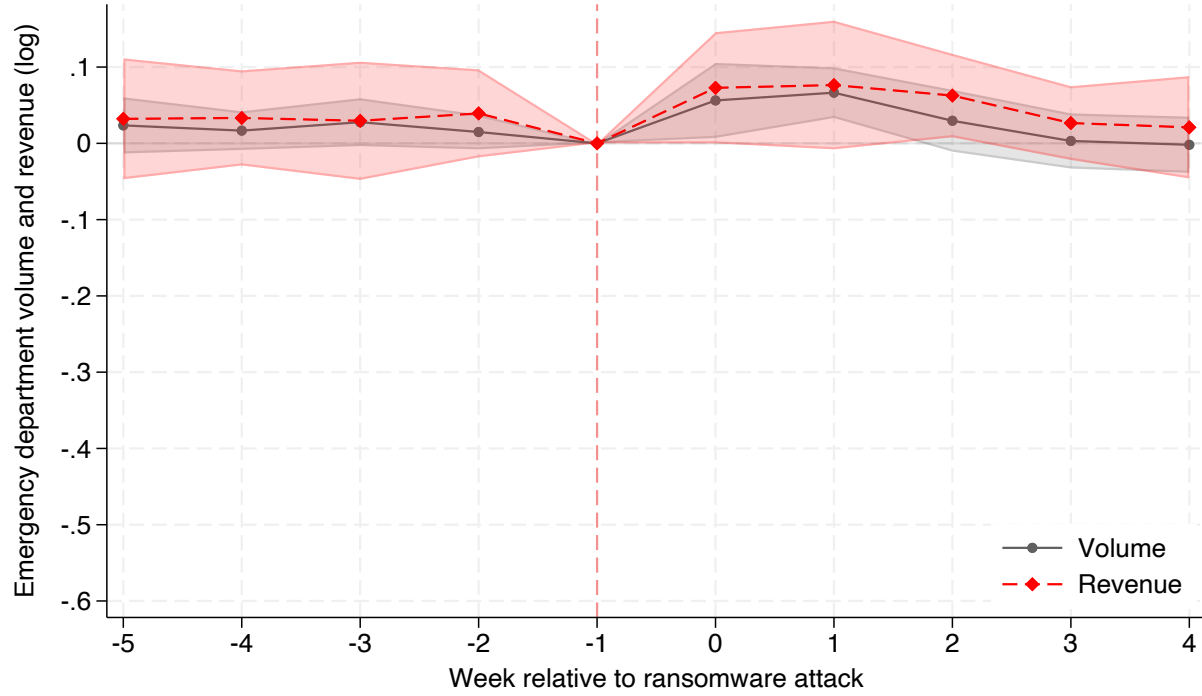
SUPPLEMENTAL APPENDIX
“HACKED TO PIECES? THE EFFECTS OF RANSOMWARE ATTACKS ON HOSPITALS AND PATIENTS”
BY HANNAH NEPRASH, CLAIRE MCGLAVE, AND SAYEH NIKPAY

FIGURE A.1 EFFECT OF RANSOMWARE ATTACKS ON VOLUME AND REVENUE AT RANSOMWARE-ATTACKED HOSPITALS



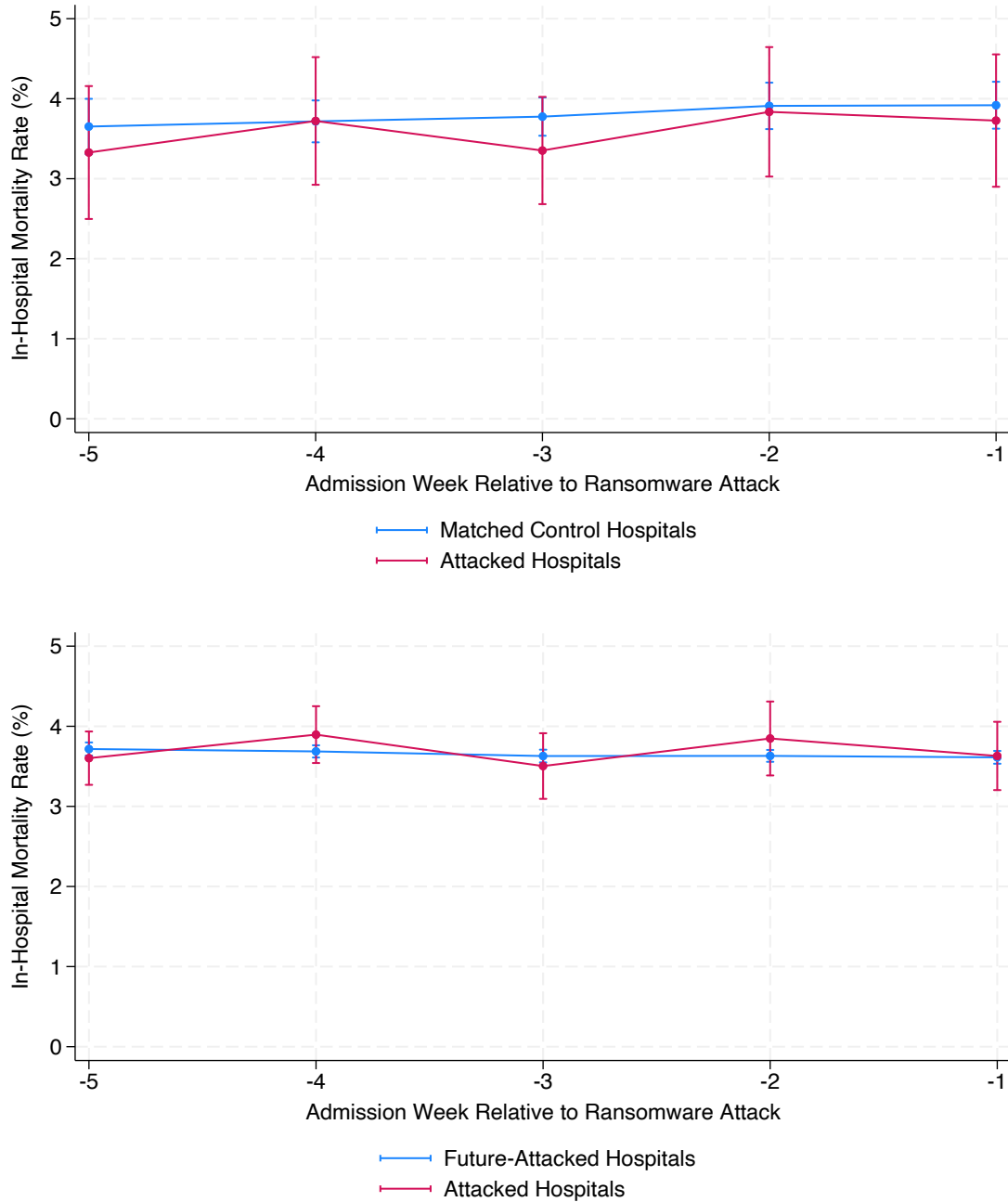
Note: This figure plots estimates of the effect of ransomware attacks on hospital volume and revenue, plotting estimates of δ_r coefficients from Equation 1. The shaded regions show 95% confidence intervals. The week prior to the attack is the reference period. Regressions are weighted by Medicare volume in the relevant setting (inpatient, ER, outpatient) in the year prior to attack. Control hospitals comprise those that would subsequently experience ransomware attacks ≥ 5 weeks in the future.

Figure A.2. EFFECT OF RANSOMWARE ATTACKS ON ER VOLUME AND REVENUE AT NEAREST-NEIGHBOR HOSPITALS



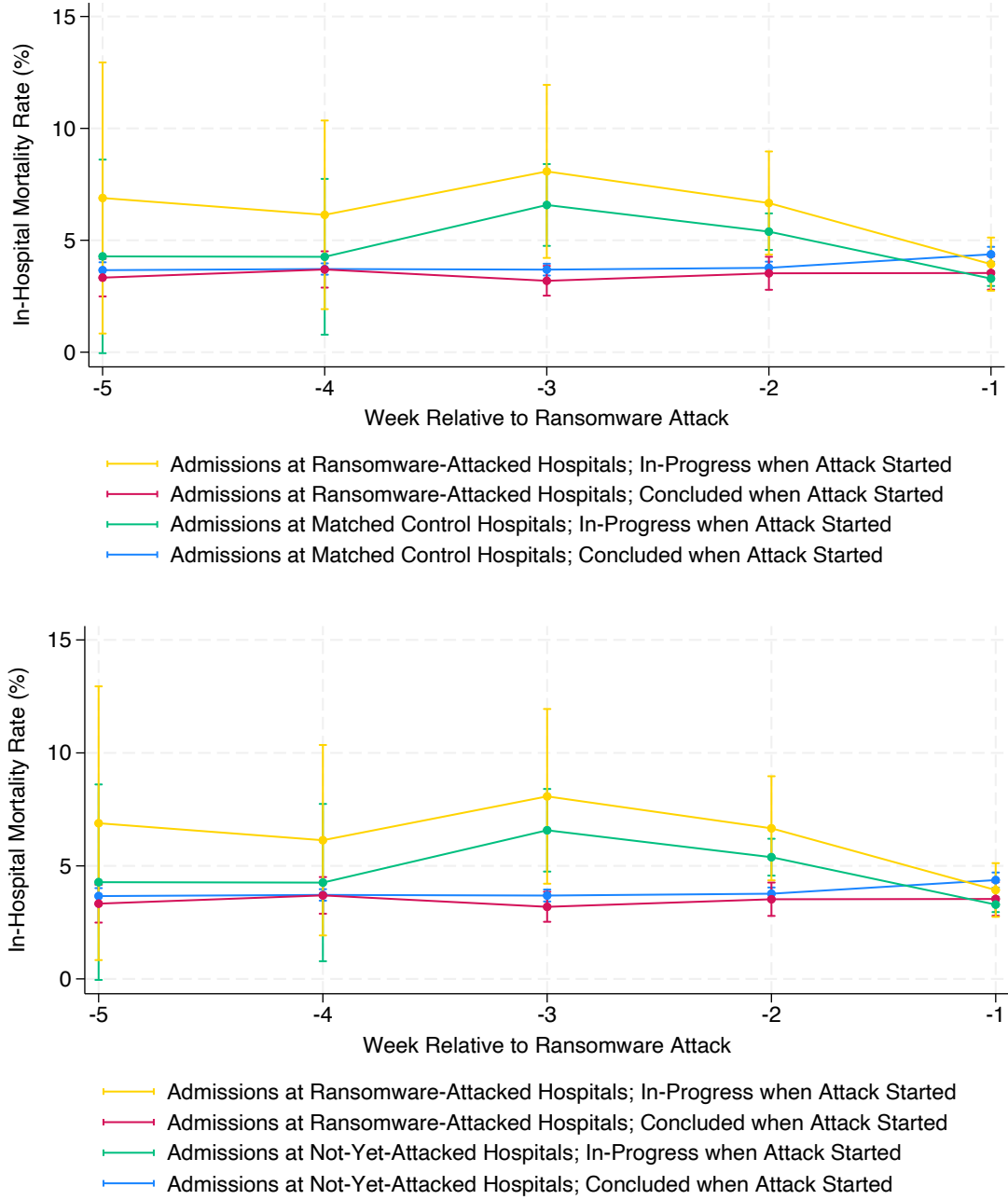
Notes: This figure plots estimates of the effect of ransomware attacks on emergency room (ER), inpatient, and outpatient hospital volume and Medicare revenue. Specifically, the figure plots estimates of δ_{τ} coefficients from Equation 1. Shaded regions show 95 percent confidence intervals. The week prior to the attack is the reference period. Regressions are weighted by Medicare volume in the relevant setting (i.e., inpatient admissions, ER visits, outpatient visits) in the year prior to ransomware attack.

FIGURE A.3. PRE-ATTACK IN-HOSPITAL MORTALITY AT TREATED AND CONTROL HOSPITALS



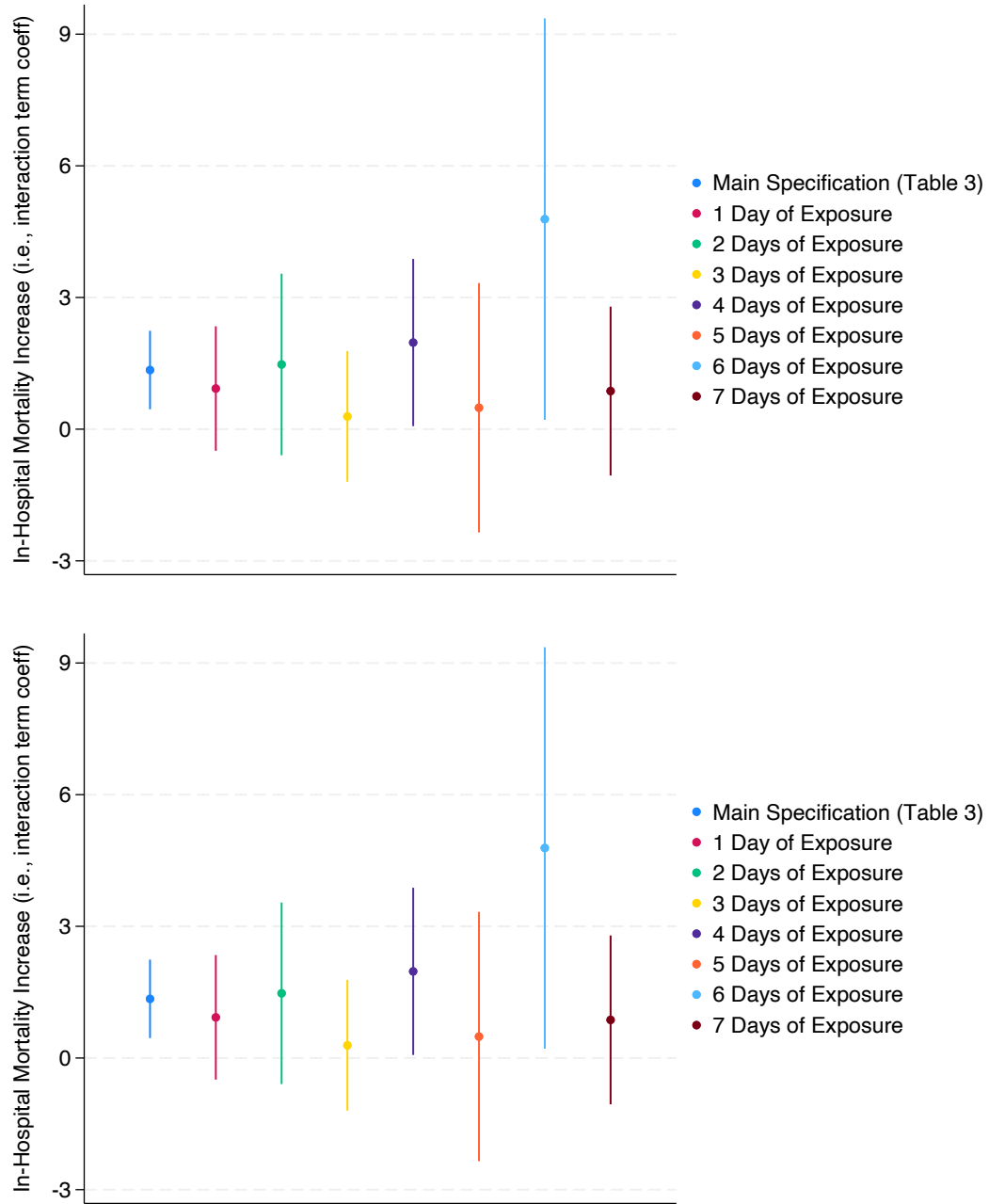
Note: This figure plots the marginal effects from an admission-level regression of in-hospital mortality (equal to 1 if the patient died in the hospital; 0 otherwise) on the interaction of admission week relative to ransomware attack and an indicator for whether the admission occurred at a treated (i.e., ransomware-attacked) or control hospital, admission characteristics (patient age, patient sex, patient race, whether the patient is dually eligible for Medicaid and Medicare, chronic condition count in the year prior to admission, whether the admission involves treatment in the intensive care unit, whether the admission is elective, whether the admission involves a primary diagnosis of acute cardiovascular event including heart attack/sepsis/stroke, and DRG weight), and time fixed effects (day-of-the-week, calendar month-by-year indicators). Panel A uses the main control group (i.e., admissions at matched hospitals in the same state, but different HRR as attacked hospitals), while Panel B uses the alternative control group (i.e., admissions at hospitals experiencing ransomware attacks ≥ 5 weeks in the future).

FIGURE A.4. IN-HOSPITAL MORTALITY RATE BY ADMISSION WEEK RANSOMWARE ATTACK, BY ADMISSION HOSPITAL TYPE AND WHETHER ADMISSION HAD CONCLUDED OR WAS STILL IN-PROGRESS AT RANSOMWARE ATTACK START



Note: This figure plots the average weekly in-hospital mortality for admissions in four groups: admissions at ransomware-attacked hospitals that were in-progress when the attack started, admissions at ransomware-attacked hospitals that were concluded when the attack started, admissions at control group hospitals that were in-progress when the attack started, and admissions at control group hospitals that had concluded when the attack started – controlling for the admission-level covariates and time fixed effects in Equation 3. Panel A uses the main control group (i.e., admissions at matched hospitals in the same state, but different HRR as attacked hospitals), while Panel B uses the alternative control group (i.e., admissions at hospitals experiencing ransomware attacks ≥ 5 weeks in the future).

FIGURE A.5. BINARY SPECIFICATION OF CONTINUOUS RANSOMWARE ATTACK EXPOSURE DURATION ON IN-HOSPITAL MORTALITY



Note: This figure plots the interaction term coefficients from eight separate difference-in-differences estimations. Leftmost is the coefficient from our main specification (Equation 3). Then we have the coefficient from a model defining exposure as one if the already-admitted patient remained admitted for the first day of the initial ransomware attack week. Subsequent coefficients show differential effects of two through seven days of exposure to the initial ransomware attack week. Regression specifications are otherwise identical to Equation 3. Panel A uses the main control group (i.e., admissions at matched hospitals in the same state, but different HRR as attacked hospitals), while Panel B uses the alternative control group (i.e., admissions at hospitals experiencing ransomware attacks ≥ 5 weeks in the future).

TABLE A.1 SUMMARY STATISTICS FOR ATTACKED AND NON-ATTACKED HOSPITALS IN 2019

	(1)	(2)	(3)		
Hospital Characteristic (2019)	Ransomware- Attacked Hospitals (N=148)	Matched Non- Attacked Hospitals in the Same State and Different HRR (N=873)	All Non- Attacked Hospitals in the Same State and Different HRR (N=1926)	Col 1 vs. 2	Col 1 vs. 3
				P-Value	P-Value
Medicare admissions, mean	3,333.9	2,775.4	2,274.7	0.039	<0.001
In-hospital mortality, %	3.1%	2.7%	2.6%	0.011	<0.001
System membership, %	68.2%	67.7%	67.8%	0.896	0.913
Non-profit status, %	77.7%	79.7%	86.2%	0.574	0.004
Operates an emergency room, %	79.1%	76.4%	76.6%	0.480	0.502
Operates an obstetric unit, %	66.2%	52.9%	50.5%	0.003	<0.001
Critical Access Hospital, %	6.8%	20.4%	28.2%	<0.001	<0.001

Note: This table presents summary statistics for ransomware-attacked hospitals versus non-attacked hospitals in the same state and different Hospital Referral Region (i.e., control group hospitals). Hospital characteristics were quantified in 2019, to avoid detecting secular changes in hospital markets over time, since ransomware attacks were concentrated during 2020 and 2021.

TABLE A.2 FACTORS THAT PREDICT TIMING OF RANSOMWARE ATTACKS ON HOSPITALS

Previous Week Characteristic	Calendar Week-Year of Ransomware Attack
Inpatient admissions	0.0608 (0.0907)
Inpatient revenue	-0.0000 (0.0000)
ER visit volume	-0.0181 (0.0389)
ER revenue	0.0000 (0.0000)
Share of BIPOC inpatient admissions	-0.0628 (0.0666)
Share of dually eligible inpatient admissions	-0.0724 (0.0855)
Share of inpatient admissions for acute cardiovascular events	0.1847 (0.1335)
In-hospital inpatient mortality rate	0.6275 (0.4350)
30-day inpatient mortality rate	-0.2150 (0.2217)
30-day readmission rate	-0.0084 (0.0834)

Note: This table presents the association between each hospital characteristic and calendar week (1-52) of each ransomware attack. Conditional on experiencing a ransomware attack, we regress calendar week of the attack on characteristics from the previous week, including inpatient admission count, inpatient Medicare revenue, ER visit volume, ER Medicare revenue, share of inpatient admissions for BIPOC patients, in-hospital mortality rate, 30-day mortality rate, and 30-day readmission rate.

TABLE A.3 MARKET-LEVEL EFFECT OF RANSOMWARE ATTACKS ON HOSPITAL CASE MIX

Emergency Department Case Mix							
	Average Age	Average Chronic Condition Count	Share Dually Eligible for Medicare and Medicaid	Share BIPOC			
Attack week 1	-0.09 (0.14)	-0.01 (0.03)	0.49 (0.37)	0.14 (0.38)			
Attack week 2	0.03 (0.13)	-0.01 (0.03)	0.31 (0.41)	0.00 (0.39)			
Attack week 3	-0.16 (0.10)	0.03 (0.04)	0.60 (0.46)	-0.15 (0.33)			
Attack week 4	-0.07 (0.16)	-0.01 (0.03)	0.43 (0.42)	-0.04 (0.36)			
Attack week 5	-0.26 (0.19)	-0.05** (0.02)	0.14 (0.44)	-0.07 (0.35)			
Baseline mean	70.45	4.849	38.90	20.22			
Inpatient Admission Case Mix							
	Average Age	Average Chronic Condition Count	Share Dually Eligible for Medicare and Medicaid	Share BIPOC	Share Acute Cardiovascular Event Admissions	Share Non-Elective Admissions	Inpatient DRG Weight
Attack week 1	0.33 (0.23)	-0.02 (0.06)	-0.13 (0.96)	-0.10 (0.46)	-0.11 (0.70)	-1.62** (0.73)	-0.06*** (0.02)
Attack week 2	0.20 (0.23)	-0.06 (0.06)	0.17 (0.82)	0.43 (0.50)	-0.61 (0.58)	-0.05 (0.66)	0.01 (0.02)
Attack week 3	0.20 (0.21)	0.09 (0.07)	0.19 (0.89)	-0.31 (0.52)	0.12 (0.71)	0.50 (0.81)	-0.01 (0.02)
Attack week 4	-0.11 (0.23)	0.04 (0.06)	0.50 (1.05)	-0.20 (0.40)	-0.09 (0.77)	-1.09 (0.75)	0.01 (0.02)
Attack week 5	0.12 (0.21)	-0.01 (0.06)	0.06 (0.85)	-0.03 (0.49)	-0.23 (0.68)	-0.50 (0.71)	-0.01 (0.02)
Baseline mean	73.77	5.997	33.94	17.70	15.50	83.32	1.505

Note: This table presents estimates of the market-level effect of ransomware attacks on measures of hospital case mix. Specifically, the table presents estimates of δ_τ coefficients (for $\tau = 0, 1$, and 2) from equation (2), which is a regression of the market-level dependent variable on Health Service Area fixed effects, week-by-year fixed effects, event week indicators, and event week indicators interacted with an indicator for treatment (i.e., ransomware attack).

TABLE A.4 EFFECT OF RANSOMWARE ATTACKS ON IN-HOSPITAL MORTALITY, SPECIFICATION WITH AND WITHOUT PATIENT AND ADMISSION CHARACTERISTICS

	In-Hospital Mortality			
	No Patient or Admission Characteristics	Patient Demographics	Patient Demographics + Chronic Condition Count	Main Model
Panel A (control group: admissions at matched hospitals)				
Exposed to attack (i.e., already admitted when attack started)	0.0277*** (0.0022)	0.0273*** (0.0022)	0.0268*** (0.0021)	-0.0011 (0.0017)
Attacked hospital	-0.0055 (0.0034)	-0.0053 (0.0033)	-0.0058* (0.0033)	-0.0034 (0.0040)
Exposed to attack * attacked hospital	0.0118*** (0.0038)	0.0121*** (0.0039)	0.0119*** (0.0040)	0.0127*** (0.0044)
Observations	285,206	285,206	278,301	278,301
Dependent variable mean	0.0374	0.0374	0.0374	0.0374
Panel B (control group: admissions at future-attacked hospitals)				
Exposed to attack	0.0208*** (0.0011)	0.0205*** (0.0011)	0.0200*** (0.0011)	-0.0029*** (0.0010)
Attacked hospital	-0.0012 (0.0011)	-0.0013 (0.0011)	-0.0009 (0.0011)	-0.0013 (0.0010)
Exposed to attack * attacked hospital	0.0136*** (0.0041)	0.0138*** (0.0041)	0.0138*** (0.0042)	0.0140*** (0.0045)
Observations	1,541,840	1,541,840	1,438,350	1,438,350
Dependent variable mean	0.0364	0.0364	0.0364	0.0364

Notes: This table shows estimates of the effect of ransomware attacks on in-hospital mortality. Estimates come from the difference-in-differences specification in Equation 3. In Panel A, control admissions comprise those at matched non-attacked hospitals in the same state, but not the same HRR as the attacked hospital. In Panel B, control admissions comprise those at hospitals that would subsequently experience ransomware attacks, at least five weeks in the future. Each column subsequently includes more patient and admission characteristics. Column 1 includes only time fixed effects; column 2 adds patient demographic characteristics; column 3 adds previous year chronic condition count; and column 4 adds admission characteristics (i.e., our main specification). *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.

TABLE A.5 ALTERNATIVE SPECIFICATIONS FOR THE ADMISSION-LEVEL ANALYSIS OF IN-HOSPITAL MORTALITY

	In-Hospital Mortality	
	Main Model	Without large ransomware attacks
Panel A (control group: admissions at matched hospitals)		
Exposed to attack (i.e., already admitted when attack started)	-0.0011 (0.0017)	-0.0003 (0.0018)
Attacked hospital	-0.0034 (0.0040)	0.0009 (0.0041)
Exposed to attack * attacked hospital	0.0127*** (0.0044)	0.0115* (0.0060)
Observations	278,301	211,274
Dependent variable mean	0.0374	0.0379
Panel B (control group: admissions at future-attacked hospitals)		
Exposed to attack	-0.0029*** (0.0010)	-0.0022** (0.0009)
Attacked hospital	-0.0013 (0.0010)	-0.0023* (0.0014)
Exposed to attack * attacked hospital	0.0140*** (0.0045)	0.0126** (0.0057)
Observations	1,438,350	1,338,034
Dependent variable mean	0.0364	0.0365

Note: This table shows estimates of the effect of ransomware attacks on in-hospital mortality. Estimates come from the difference-in-differences specification in Equation 3. In Column 2 ('Main Model'), control admissions comprise those at matched hospitals in the same state, but not the same HRR as the attacked hospital. Column 3 repeats this specification, omitting two large ransomware attacks that affected multiple hospitals simultaneously: the Universal Health Services attack and the Hackensack Health System Attack. Admission-level covariates include whether the admission was elective or non-elective, whether the admission involved care in the intensive care unit, whether the admission was for an acute cardiovascular emergency, the Medicare Severity Diagnostic Related Grouping weight, patient age, patient race, patient sex, patient chronic condition count (from the year prior to hospitalization), and whether the patient was dually eligible for Medicare and Medicaid.

TABLE A.6. EFFECT OF RANSOMWARE ATTACKS ON HEALTH OUTCOMES FOR PATIENTS ALREADY ADMITTED TO NEIGHBORING NON-ATTACKED HOSPITALS AT THE TIME OF ATTACK

	In-Hospital Mortality		
	Hospitals in the Same HRR	Hospitals in the same Health Service Area	Nearest Neighbor Hospitals
Exposed to attack (i.e., already admitted when attack started)	0.0010 (0.0012)	0.0011 (0.0012)	0.0006 (0.0012)
Treated hospital	0.0016* (0.0009)	0.0018 (0.0011)	-0.0011 (0.0023)
Exposed to attack * treated hospital	0.0013 (0.0015)	0.0018 (0.0023)	0.0003 (0.0046)
Observations	1,971,201	1,971,201	1,566,720
Baseline mean	0.0400	0.0400	0.0404

Note: This table presents estimates of the effect of ransomware attacks on health outcomes, including mortality (in-hospital and within 30-days of admission) and 30-day readmissions. Estimates come from the difference-in-differences specification (Equation 3), which compares patients who were still admitted at the start of each ransomware attack to patients who had been admitted within the 35 days prior to each attack and discharged before the attack date – at neighboring non-attacked hospitals versus matched control hospitals in the same state, but not the same HRR as the attacked hospital. Admission-level covariates include whether the admission was elective or non-elective, whether the admission involved care in the intensive care unit, whether the admission was for an acute cardiovascular emergency (i.e., heart attack, sepsis, or stroke), the Medicare Severity Diagnostic Related Grouping weight, patient age, patient race, patient sex, patient chronic condition count (from the year prior to hospitalization), and whether the patient was dually eligible for Medicare and Medicaid.