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Comprehensive methodology to monitor longitudinal change patterns during EHR implementations: a case study at a large health care delivery network

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ABSTRACT

Objective: To test a systematic methodology to monitor longitudinal change patterns on quality, productivity, and safety outcomes during a large-scale commercial Electronic Health Record (EHR) implementation.

Materials and Methods: Our method combines an interrupted time-series design with control sites and 41 consensus outcomes including quality (11 measures), productivity (20 measures), and safety (10 measures). The intervention consisted of a phased commercial EHR implementation at a large health care delivery network. Four medium-size hospitals and 39 clinics from 5 geographic regions implementing the new EHR were compared against a parallel control consisting of one medium-size and one large hospital and 10 clinics that had not implemented the new EHR at the time of this study. We collected monthly data from February 2013 to July 2017.

Results: The proposed methodology was successfully implemented and significant changes were observed in most measured variables. A significant change attributable to the intervention was observed in 12 (29%) measures in three or more regions; in 32 (78%) measures in two or more regions; and in 40 (98%) measures in at least one region. A similar pattern (i.e., same impact in three or more regions) was detected for nine (22%) measures, a mixed pattern (i.e., same impact in two regions, and different impact in other regions) was detected for nine (22%) measures, and an inconsistent pattern (i.e., did not detect the same impact across regions) was detected for 23 (56%) measures.

Discussion: Using a formal methodology to assess changes in a set of consensus measures, we detected various patterns of impact and mixed time-sensitive effects. With an increasing adoption of EHR systems, it is critical for health care organizations to systematically monitor their EHR implementations. The proposed method provides a robust and consistent approach to monitor EHR implementations longitudinally allowing for continuous monitoring after the system becomes stable in order to avoid unexpected effects.

Conclusion: Our results and methodology can guide the broader medical and informatics communities by informing *what* and *how* to continuously monitor EHR impact on quality, productivity, and safety.

1. Background and significance

Although Electronic Health Record (EHR) systems have recently achieved widespread adoption in the U.S. [1,2], investigations of their impact rarely focus on the effects introduced by EHR implementations, and have not contributed to increasing our understanding of the impact of EHRs on care outcomes [3]. The literature investigating such an impact is also increasing [4,5]; however, current evaluations frequently produce mixed or even negative results [6,7], leaving unanswered questions as to the impact of health information technology (health IT) adoption [8]. Contributing factors to these gaps include poor descriptions of context of the settings and interventions tested, and the use of a narrow set of study-specific measurements, creating obstacles to the comparison of outcomes across studies [9]. In addition, despite the fact that EHR implementations introduce sociotechnical changes that iteratively evolve over time [10], exposing users to a learning curve of

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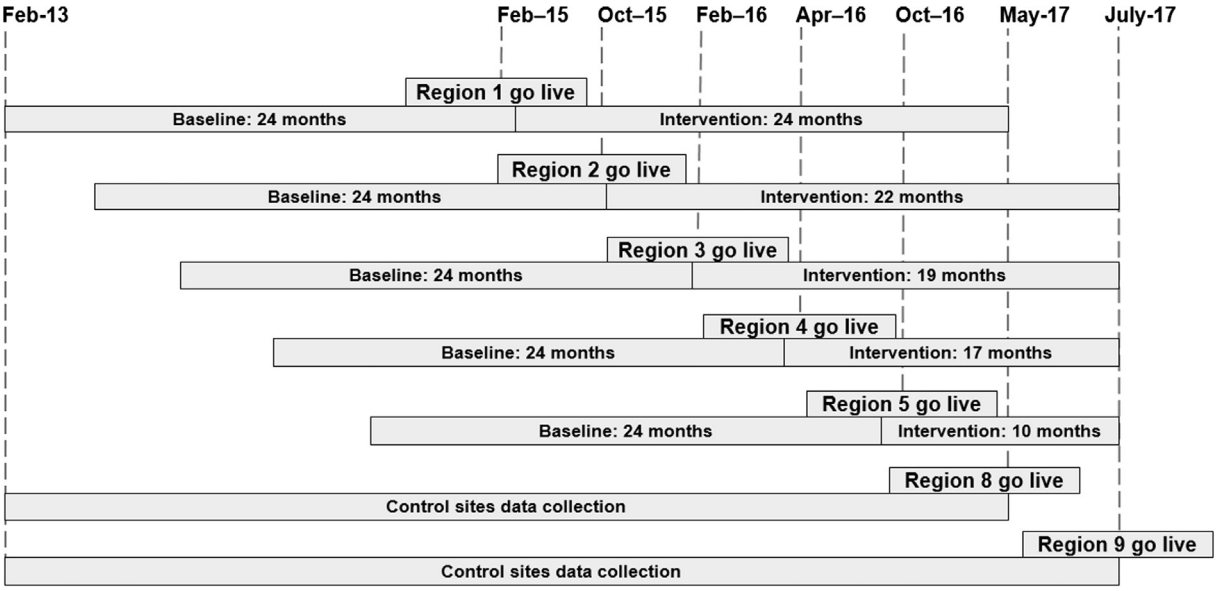

Fig. 1. Illustration of study design and EHR go live in intervention and control regions.

up to two years [11], health IT evaluations frequently use simple research designs such as pretest-posttest comparisons that do not consider the longitudinal characteristic of EHR implementations [12–15]. There is a need to overcome these methodological limitations to: (1) increase the capacity of future systematic reviews – and potential meta-analyses – to compare context-related information, interventions, and outcomes across studies; and (2) improve our understanding of the impact of health IT interventions on quality, productivity, and safety outcomes with continuous and systematic monitoring of such interventions [3,5].

We have developed a systematic methodology to detect near real-time performance changes during EHR implementations [16]. The methodology includes a robust inventory of outcome measures likely impacted by health IT interventions. The measures were retrieved from the literature [9] and suggested by subject-matter experts [17]. Our method was previously used in a pilot longitudinal analysis of a commercial EHR implementation [16]. In the present study, we expand our analysis by assessing more measures and care settings from geographically dispersed regions of the same implementation.

2. Objective

The objective of this study is to test a systematic and potentially replicable methodology to monitor longitudinal change patterns during EHR implementations. Health IT interventions – especially implementation of multifunctional commercial EHR systems – are highly complex interventions consisting of multiple small interventions. In this study, we aimed to demonstrate that the proposed methodology can both prospectively and retrospectively identify patterns of impact at an organization implementing an EHR; we do not focus on evaluating whether clinical impacts can be attributed to the new EHR, nor do we

Table 1
Detailed description of ambulatory measures.

Measure	Description	Criteria
Quality of care measures		
Blood pressure control	Rate of diabetes patients with blood pressure under control	N: diabetes patients with blood pressure under control D: diabetes patients with blood pressure measured
Diabetes Bundle	Composite measure for diabetes control	N: patients in compliance with all diabetes bundle items (hemoglobin A1c; blood pressure; retinopathy screening; nephropathy screening) D: eligible diabetes patients
Hemoglobin A1c control	Rate of diabetes patients with hemoglobin A1c under control	N: diabetes patients with Hemoglobin A1c below 8% D: diabetes patients with Hemoglobin A1c measured
Medication for Asthma	Rate of asthma patients using appropriate medication	N: asthma patients who received controller reliever medication D: eligible asthma patients
Productivity measures		
Employee movement rate	Rate of employees moved permanently to a different facility or department	N: ambulatory employees transferred to a different work location D: total ambulatory employees
Employee turnover rate	Rate of employee contracts terminated	N: ambulatory employees with voluntary contract termination D: total ambulatory employees
Laboratory test orders	Number of orders of laboratory tests	Number of orders of laboratory tests
New patient visits	Rate of new patient (new to Intermountain Healthcare) visits to ambulatory settings	N: new patient visits D: total patient visits
Patient visits	Number of patient visits to ambulatory settings	Number of patient visits to ambulatory care clinics
Radiology test orders	Number of orders of imaging tests	Number of imaging tests completed
Time documenting in EHR	Average time spent by provider documenting in electronic health records per patient	Average time spent per provider documenting (any interaction within a patient chart) in electronic health records per patient – Monday to Friday – 8 am to 6 pm
Time documenting in EHR after hours	Time spent by provider documenting in electronic health records after work hours	Average time spent per provider documenting (any interaction within a patient chart) in electronic health records per patient after 6 pm

Abbreviations: N: numerator; D: denominator.

Table 2
Detailed description of hospital measures.

Measure	Description	Criteria
Quality of care measures		
Hospital LOS	Length of stay of hospitalized patients	Average hospital length of stay in days
Mortality rate	Rate of patients who died during hospitalization	N: patients who died during hospitalization D: total patients hospitalized
NICU admissions	Number of patients admitted to newborn intensive care unit	Number of patients admitted to newborn intensive care unit
NICU LOS	Average length of stay of newborn intensive care unit patients	Average length of stay of newborn intensive care unit patients in days
Patient satisfaction rate	Rate of patients who gave their hospital a rating of 9 or 10 on a scale from 0 (lowest) to 10 (highest)	N: patients who rated the hospital they were admitted as 9 or 10 D: patients who answered the survey
Pressure ulcer rate	Rate of patients who developed pressure ulcer during hospitalization	N: inpatient pressure ulcer cases D: 100 total inpatient discharges
Readmission rate	Rate of heart failure patients readmitted within 30 days	N: unplanned heart failure readmissions D: 100 unplanned heart failure patient discharges
Productivity measures		
ED LOS	Length of stay of patients in emergency departments	Median length of stay of patients in the emergency department in hours
ED visits	Number of patient visits to emergency departments	Number of emergency department visits
ED wait time	Mean time between patient arrival and seen by provider in emergency departments	Median time between patient check-in and seen by provider in the emergency department
Electronic orders rate	Rate of orders entered electronically by provider	Rate of orders entered by provider on electronic health record system
Employee movement rate	Rate of employees moved permanently to a different facility or department	N: hospital employees transferred to a different work location D: total hospital employees
Employee turnover rate	Rate of employee contracts terminated	N: hospital employees with voluntary contract termination D: total hospital employees
Hospitalizations	Number of patients hospitalized	Number of patients hospitalized
Laboratory test orders	Number of orders of laboratory tests	Number of orders of laboratory tests
Radiology test orders	Number of imaging tests	Number of imaging tests completed
Time documenting in EHR	Time spent by provider documenting in electronic health records per patient	Average time spent per provider documenting (any interaction within a patient chart) in electronic health records per patient
Time to complete radiology tests	Mean time between radiology test started and completed	Mean time between patient arrival and imaging test completed in minutes
Time to sign radiology tests	Mean time between radiology test completed and report signed by radiologist	Mean time for signing imaging test report in hours
Patient safety measures		
Abdominal hysterectomy infection rate	Rate of hospital-acquired surgical site infections for abdominal hysterectomy surgeries	N: abdominal hysterectomy infections D: abdominal hysterectomy procedures
ADEs rate	Rate of adverse drug events	N: adverse drug events D: 1000 inpatient days
Bloodstream infection rate	Rate of hospital-acquired central line associated bloodstream infections	N: central line associated bloodstream infections D: 1000 central line days
Colon surgery infection rate	Rate of hospital-acquired surgical site infections for colon surgeries	N: colon surgery infections D: colon surgery procedures
Fall rate	Rate of patient falls during hospitalization	N: patient falls D: 1000 inpatient days
Hospital-acquired CDiff infection rate	Rate of hospital-acquired infections caused by Clostridium Difficile	N: Clostridium Difficile infections D: 10,000 inpatient days
Hospital-acquired CRA infection rate	Rate of hospital-acquired infections caused by Carbapenem-resistant Acinetobacter	N: CRA infections D: 10,000 inpatient days
Hospital-acquired infection MRSA rate	Rate of hospital-acquired infections caused by Methicillin-resistant Staphylococcus aureus	N: MRSA infections D: 10,000 inpatient days
Hospital-acquired VRE infection rate	Rate of hospital-acquired infections caused by Vancomycin-resistant Enterococci	N: VRE infections D: 10,000 inpatient days
Urinary tract infection rate	Rate of hospital-acquired Foley catheter-associated urinary tract infections	N: catheter-associated urinary tract infections D: 1000 Foley catheter days

Abbreviations: N: numerator; D: denominator.

focus on comparing legacy systems with the new EHR. We define patterns of impact as outcome trends (e.g., significant decrease after EHR "go live", followed by recovery to the baseline after 2 years) that were similar across different implementation regions.

3. Materials and methods

3.1. Description of intervention

Intermountain Healthcare, a not-for-profit, integrated care delivery system of 22 hospitals and over 185 clinics covering Utah and southern Idaho is replacing a group of long-used and stable homegrown legacy systems [18,19] with the commercial Millennium EHR (Cerner Corporation, Kansas City, MO, U.S.). The implementation follows a phased approach with the introduction of the new EHR across 10 dispersed geographical regions. The implementation in each region follows a "big bang" strategy, replacing all legacy systems at once within that region. EHR capabilities involved in the implementation include: computerized provider order entry (CPOE); clinical decision support (CDS) systems; clinical documentation; problem lists; patient medical history; patient demographics; scheduling, admission, transfer and discharge; radiology information system (RIS); medication reconciliation; medication dispensing; clinical pharmacy; electronic medication administration; infectious disease management; and laboratory results.

3.2. Design and settings

We used an interrupted time-series design with the intervention implemented (i.e., EHR "go live") at the first five regions at different points in time (Fig. 1). In addition, we had control sites from two regions where the EHR was implemented only at the end of the study. Data were analyzed monthly from February 2013 to July 2017. Each

Table 3
Examples of measures that followed similar, mixed, and inconsistent patterns.

Measure	Impact
Similar pattern	
Blood pressure control	Decreased significantly immediately after the go live in regions 2, 3, 4, and 5, followed by a recovery to the baseline levels observed before the intervention in two regions within 7 to 16 months
New patient visits	Decreased significantly immediately after the go live in regions 1, 2, 4, and 5. No region recovered to the baseline levels observed before the intervention
Laboratory test orders	Decreased significantly immediately after the go live in regions 1, 3, 4, and 5. No region recovered to the baseline levels observed before the intervention
ED LOS	Increased significantly immediately after the go live in regions 1, 2, 4, and 5. All regions recovered to the baseline levels observed before the intervention within 10 to 15 months, except for region 2
ED wait time	Increased significantly immediately after the go live in regions 2, 4, and 5. All regions recovered to the baseline levels observed before the intervention within 7 to 12 months
Mixed pattern	
Hospital-acquired CDiff infection rate	Decreased significantly immediately after the go live in regions 1 and 2 and per month in regions 2 and 4; whereas in region 5 it increased significantly per month
Inconsistent pattern	
Medication for asthma	Increased significantly per month only in region 2

Abbreviations: CDiff: Clostridium Difficile; ED: emergency department; LOS: length of stay.

intervention region included a two-year baseline period before the EHR go live, followed by a 10–24-month intervention period, which ended when the control sites went live (July 2017). Each intervention region includes one hospital with 100 or more beds (except region 3, which has no hospitals fitting the inclusion criteria) and 5–10 primary care clinics with the specialties Family Medicine, Internal Medicine, or Pediatrics. The distribution of settings per intervention region is as follows: region 1: 5 primary care clinics and 1 hospital (140 beds); region 2: 7 primary care clinics and 1 hospital (312 beds); region 3: 9 primary care clinics; region 4: 10 primary care clinics and 1 hospital (375 beds); and region 5: 8 primary care clinics and 1 hospital (245 beds). The two control regions include one medium-size hospital (243 beds), one large hospital (472 beds), and 10 primary care clinics. We excluded children's hospitals and specialty care clinics because they have specific populations and outcomes not easily generalizable to other settings.

Each intervention region was analyzed separately and its settings were compared with one hospital (except region 3) and the same number of primary care clinics selected from the control regions. Due to the high cost and complexity of large EHR implementations, the timeline of settings to be implemented in such projects is naturally a business-driven decision, and, as a result, selection of control sites is limited by such business constraints. We were able to select control sites from two of the last regions receiving the implementation. Control hospitals were selected based on clinical setting (i.e., tertiary care hospital), hospital size (i.e., 100 or more beds), and availability as a control site for a minimum of 10 months in parallel with an intervention site. Control clinics were selected based on approximate average of monthly visits, availability as control site, services offered (e.g., imaging services), and primary care population served (e.g., diabetes, asthma, pediatrics). Fig. 1 illustrates study design and implementation phases. Detailed characteristics of study settings can be found in Table 1 in the online Supplement. Intermountain Healthcare institutional review board approved this study.

3.3. Outcome measurements

We monitored 41 outcomes including quality (11 measures), productivity (20 measures), and safety (10 measures). Twelve measures assessed ambulatory outcomes and 29 measures assessed hospital outcomes. The measures were retrieved from an inventory of outcome measures likely impacted by health IT interventions with data readily available in electronic format [17]. Data were collected monthly from existing business intelligence reports and Intermountain's enterprise data warehouse. We collected data for measures with data available before and after the go live except for EHR use-related measures such as time documenting in the EHR during and after work hours and electronic orders rate; these measures were not available in the legacy systems and were assessed only among intervention regions without a baseline or control. We chose to include these measures because they are frequently used to assess clinician workload [20]. Detailed descriptions of study measures can be found in Tables 1 and 2.

3.4. Data analysis

We used an interrupted time-series analysis (ITSA) with an ordinary least squares model (OLS) [21], with the Newey-West autocorrelation test [22], adjusting the number of lags according to the Cumby-Huizinga general test for autocorrelation [23]. Based on actual monthly data points, the model generates two trend lines that represent the average change (increase/decrease) per month in the periods before and after the intervention, and produces two tests: (1) the *immediate* effect; and (2) the *over time* effect. The immediate effect is the change in the level of the trend line in the month after the introduction of the intervention. The immediate effect is calculated as the difference between the last value of the trend line generated by the model before the intervention and the first value of the trend line after the intervention. The over time effect measures a change in the slope of the trend line after the intervention. It is calculated as the difference between the monthly change (average increase/decrease per month) before and after the intervention. Both tests are calculated in each group (intervention/control) separately, and then the difference between the two groups is obtained: ((intervention after – intervention before) – (control after – control before)). Measures from clinics in the same region were aggregated in terms of their arithmetic average. Data analysis was performed using Stata version 14.2 statistical software [StataCorp LP, College Station, TX].

4. Results

The proposed methodology was successfully implemented and significant changes were observed in most measured variables. A significant change in the intervention sites when compared to the control sites was observed in 12 (29%) measures in three or more regions; in 32 (78%) measures in two or more regions; and in 40 (98%) measures in at least one region. In addition, 20 (49%) measures detected a significant difference between the two groups caused by a significant change that happened in the control sites; out of these, 7 (17%) detected a significant difference in two regions, and 13 (32%) measures detected a significant difference in one region. Three patterns of impact across implementation regions were identified: *similar pattern:* measures

Table 4
Immediate effect for ambulatory care measures.

Measure	Region 1 vs. Control Coefficient (95% CI)	p Value	Region 2 vs. Control Coefficient (95% CI)	p Value	Region 3 vs. Control Coefficient (95% CI)	p Value	Region 4 vs. Control Coefficient (95% CI)	p Value	Region 5 vs. Control Coefficient (95% CI)	p Value
Quality of care measures										
Blood pressure control[a,b]	–	–	−3.33 (−5.82, −0.85)	0.009	−2.55 (−3.66, −1.43)	< 0.001	−3.63 (−5.17, −2.08)	< 0.001	−3.32 (−5.35, −1.30)	0.002
Diabetes bundle[a]	–	–	−2.89 (−6.18, 0.39)	0.08	−4.28 (−7.48, −1.08)	0.009	−1.44 (−4.39, 1.50)	0.33	−8.53 (−12.37, −4.70)	< 0.001
Hemoglobin A1c control	−3.11 (−4.45, −1.77)	< 0.001	−0.57 (−1.83, 0.68)	0.36	2.04 (−0.72, 4.80)	0.14	3.79 (1.09, 6.49)	0.01[d]	−0.01 (−1.97, 1.94)	0.98
Medication for asthma	−26.04 (−38.86, −13.21)	< 0.001[d]	−1.65 (−9.14, 5.84)	0.66	9.27 (−2.39, 20.94)	0.11	−2.06 (−9.56, 5.43)	0.58	6.88 (−7.34, 21.12)	0.33
Productivity measures										
Employees movement rate	−0.67 (−1.41, 0.06)	0.07	0.69 (0.14, 1.25)	0.01[d]	−1.49 (−2.62, −0.36)	0.01	−1.00 (−2.36, 0.35)	0.14	0.95 (−0.39, 2.30)	0.16
Employee turnover rate	0.69 (−0.48, 1.88)	0.24	−1.03 (−1.71, −0.36)	0.003	−0.70 (−2.24, 0.83)	0.36	−0.25 (−1.85, 1.34)	0.75	1.04 (0.27, 1.80)	0.008
Laboratory test orders[b]	−317.91 (−407.35, −228.47)	< 0.001	20.78 (−167.93, 209.50)	0.82	−293.74 (−355.24, −232.24)	< 0.001	−157.40 (−268.33, −46.46)	0.006	−796.37 (−898.07, −694.68)	< 0.001
New patient visits[b]	−1.01 (−1.59, −0.44)	0.001	−2.18 (−2.87, −1.50)	< 0.001	−0.71 (−2.57, 1.14)	0.44	−1.06 (−1.98, −0.14)	0.02	−2.90 (−4.05, −1.75)	< 0.001
Patient visits	462.59 (370.66, 554.53)	< 0.001[d]	34.57 (−105.71, 174.86)	0.62	−18.02 (−64.25, 28.20)	0.44	−178.88 (−244.45, −113.32)	< 0.001	−116.04 (−239.96, 7.88)	0.07
Radiology test orders[c]	−61.29 (−102.75, −19.83)	0.004	−27.46 (−51.54, −3.38)	0.02	13.86 (4.81, 22.92)	0.003[d]	–	–	−1.92 (−18.62, 14.78)	0.81

Abbreviations: CI: confidence interval.
[a] We were not able to collect data for blood pressure and diabetes bundle in region 1 due to ongoing database mapping efforts.
[b] Denotes measures with a similar significant immediate effect in 3 or more regions.
[c] We were not able to collect data for radiology tests in region 4 due to a different parametrization of radiology data in that region.
[d] Denotes a significance difference between the two groups caused by a significant difference that happened in the control sites.

Table 5
Over time effect for ambulatory care measures.

Measure	Region 1 vs. Control Coefficient (95% CI)	p Value	Region 2 vs. Control Coefficient (95% CI)	p Value	Region 3 vs. Control Coefficient (95% CI)	p Value	Region 4 vs. Control Coefficient (95% CI)	p Value	Region 5 vs. Control Coefficient (95% CI)	p Value
Quality of care measures										
Blood pressure control[a,b]	–	–	0.40 (0.24, 0.55)	< 0.001[e]	0.52 (0.42, 0.63)	< 0.001	0.40 (0.27, 0.53)	< 0.001	1.47 (1.24, 1.71)	< 0.001
Diabetes bundle[a]	–	–	0.45 (0.21, 0.69)	< 0.001[e]	0.41 (0.21, 0.62)	< 0.001	−0.38 (−0.65, −0.10)	0.007	−0.71 (−1.00, −0.43)	< 0.001
Hemoglobin A1c control	−0.15 (−0.26, −0.03)	0.01	0.22 (0.11, 0.32)	< 0.001[e]	0.13 (−0.11, 0.39)	0.28	−0.07 (−0.36, 0.20)	0.58	−1.11 (−1.32, −0.89)	< 0.001
Medication for asthma	−0.21 (−1.24, 0.82)	0.68	2.57 (1.96, 3.17)	< 0.001	0.25 (−0.98, 1.48)	0.68	−0.04 (−0.80, 0.70)	0.89	−3.18 (−4.78, −1.59)	< 0.001
Productivity measures										
Employees movement rate[b]	0.07 (0.01, 0.13)	0.01	0.08 (0.04, 0.12)	< 0.001	0.22 (0.11, 0.33)	< 0.001	0.18 (0.08, 0.29)	0.001[e]	0.19 (−0.03, 0.42)	0.08
Employee turnover rate	0.12 (0.03, 0.21)	0.007	0.01 (−0.04, 0.05)	0.73	0.03 (−0.09, 0.17)	0.56	−0.08 (−0.22, 0.05)	0.23	−0.13 (−0.21, −0.05)	0.001
Laboratory test orders	2.84 (−3.57, 9.27)	0.38	−24.44 (−41.11, −7.78)	0.005	33.12 (26.24, 39.99)	< 0.001[e]	2.89 (−10.83, 16.63)	0.67	54.84 (37.45, 72.23)	< 0.001[e]
New patient visits	−0.18 (−0.02, −0.10)	0.001	−0.01 (−0.05, 0.04)	0.82	0.01 (−0.15, 0.17)	0.90	−0.02 (−0.11, 0.05)	0.51	0.10 (0.01, 0.20)	0.03[e]
Patient visits	−5.59 (−12.14, 0.96)	0.09	−7.61 (−19.65, 4.43)	0.21	8.60 (4.28, 12.92)	< 0.001	13.82 (6.55, 21.08)	< 0.001	4.04 (−14.36, 22.44)	0.66
Radiology test orders[c]	3.45 (0.70, 6.19)	0.01[e]	−1.84 (−3.99, 0.29)	0.09	1.20 (0.37, 2.02)	0.005[e]	–	–	−1.75 (−4.61, 1.10)	0.22
Time documenting in EHR[d]	−0.01 (−0.06, 0.06)	0.91	−0.07 (−0.18, 0.02)	0.14	−0.13 (−0.31, 0.05)	0.16	−0.15 (−0.37, 0.06)	0.15	−0.87 (−1.68, −0.07)	0.03
Time documenting in EHR after hours[d]	0.01 (−0.01, 0.02)	0.55	0.01 (−0.01, 0.01)	0.94	0.01 (−0.01, 0.02)	0.43	0.02 (0.01, 0.04)	0.03	0.12 (−0.04, 0.29)	0.15

Abbreviations: CI: confidence interval; EHR: electronic health records.
[a] We were not able to collect data for blood pressure and diabetes bundle in region 1 due to ongoing database mapping efforts.
[b] Denotes measures with a similar significant over time effect in 3 or more regions.
[c] We were not able to collect data for radiology tests in region 4 due to a different parametrization of radiology data in that region.
[d] Time documenting in EHR and time documenting in EHR after hours were assessed without control sites.
[e] Denotes a significant difference between the two groups caused by a significant difference that happened in the control sites.

Table 6
Immediate effect for hospital measures.

Measure	Region 1 vs. Control Coefficient (95% CI)	p Value	Region 2 vs. Control Coefficient (95% CI)	p Value	Region 4 vs. Control Coefficient (95% CI)	p Value	Region 5 vs. Control Coefficient (95% CI)	p Value
Quality of care measures								
Hospital LOS	−0.13 (−0.28, 0.01)	0.06	0.04 (−0.03, 0.11)	0.24	−0.09 (−0.40, 0.20)	0.52	0.21 (0.14, 0.29)	< 0.001
Mortality rate	0.46 (0.22, 0.69)	< 0.001	−0.03 (−0.34, 0.26)	0.79	0.35 (0.02, 0.68)	0.03[d]	0.10 (−0.22, 0.43)	0.53
NICU admissions	11.18 (6.22, 11.18)	< 0.001	11.93 (1.98, 21.87)	0.01	0.18 (−8.17, 8.55)	0.96	0.60 (−4.78, 5.99)	0.82
NICU LOS	−1.30 (−2.53, −0.07)	0.04	0.14 (−1.36, 1.66)	0.84	−0.86 (−2.91, 1.17)	0.40	−2.35 (−5.59, 0.88)	0.15
Patient satisfaction rate	−1.03 (−3.07, 0.99)	0.31	−1.25 (−3.51, 1.00)	0.27	−0.24 (−2.51, 2.03)	0.83	−1.89 (−3.87, 0.08)	0.06
Pressure ulcer rate	0.08 (−0.06, 0.22)	0.25	−0.23 (−0.39, −0.07)	0.005	0.01 (−0.23, 0.24)	0.94	−0.03 (−0.30, 0.23)	0.78
Readmission rate	−3.47 (−18.76, 11.81)	0.65	−6.82 (−13.55, −0.10)	0.05[d]	−7.11 (−13.80, −0.42)	0.04	−0.53 (−12.41, 11.34)	0.98
Productivity measures								
ED LOS[a]	0.18 (0.02, 0.33)	0.02	0.53 (0.47, 0.59)	< 0.001	0.46 (0.33, 0.59)	< 0.001	0.50 (0.36, 0.64)	< 0.001
ED visits	−51.81 (−201.70, 98.07)	0.49	117.18 (−83.92, 318.29)	0.25	214.45 (83.60, 345.30)	0.002	378.62 (224.79, 532.46)	< 0.001[d]
ED wait time[a]	1.96 (−0.84, 4.76)	0.16	9.37 (5.95, 12.78)	< 0.001	9.36 (6.83, 11.90)	< 0.001	8.44 (4.87, 12.00)	< 0.001
Employees movement rate	0.22 (−0.10, 0.56)	0.17	0.12 (−0.42, 0.68)	0.64	0.11 (−0.36, 0.60)	0.63	−0.74 (−1.14, −0.33)	0.001
Employee turnover rate	−0.11 (−0.32, 0.08)	0.26	0.27 (0.06, 0.47)	0.01[d]	0.33 (0.08, 0.59)	0.009	0.33 (0.05, 0.62)	0.01
Hospitalizations	2.89 (−42.77, 48.55)	0.90	9.48 (−45.89, 64.86)	0.73	21.54 (−111.74, 154.84)2	0.74	171.28 (103.10, 239.46)	< 0.001
Laboratory test orders	−1820.99 (−3396.21, −245.76)	0.02	15460.20 (10313.50, 20606.89)	< 0.001[d]	704.64 (−5328.30, 6737.58)	0.81	5066.42 (1440.93, 8691.91)	0.007
Radiology test orders	−259.10 (−464.31, −53.88)	0.01	2.34 (−353.76, 358.45)	0.99	−285.01 (−652.81, 82.78)	0.12	279.27 (−1923.25, 750.80)	0.24
Time to complete radiology tests[a,b]	−2.75 (−3.66, −1.85)	< 0.001	−6.50 (−8.30, −4.71)	< 0.001	–	–	−2.53 (−3.61–1.45)	< 0.001
Time to sign radiology tests	−0.30 (−0.65, 0.05)	0.09	0.40 (0.23, 0.57)	< 0.001	−.0.15 (−0.32, 0.17)	0.08	−0.49 (−0.61, −0.36)	< 0.001
Patient safety measures								
Abdominal hysterectomy infection rate[c]	4.16 (−0.35, 8.69)	0.07	0.80 (−0.45, 2.06)	0.20	−2.68 (−9.24, 3.88)	0.41	–	–
ADEs rate	1.17 (0.19, 2.16)	0.02	1.69 (−0.10, 3.49)	0.06	2.74 (0.93, 4.55)	0.003[d]	−0.25 (−2.87, 2.36)	0.84
Bloodstream infection rate	−1.11 (−4.01, 1.77)	0.44	0.21 (−0.19, 0.63)	0.29	−0.01 (−0.26, 0.26)	0.99	−0.19 (−0.69, 0.29)	0.42
Colon surgery infection rate	3.68 (−4.80, 12.17)	0.39	−2.32 (−14.44, 9.79)	0.70	−0.84 (−5.34, 3.65)	0.71	1.31 (−8.02, 10.65)	0.77
Falls rate	0.76 (−0.45, 1.98)	0.21	−0.84 (−1.40, −0.29)	0.003	0.43 (−0.48, 1.35)	0.34	−0.48 (−1.14, 0.17)	0.14
Hospital-acquired CDiff infection rate	−7.11 (−14.37, 0.13)	0.05	−6.07 (−8.32, −3.82)	< 0.001	−2.63 (−5.36, 0.08)	0.06	−4.81 (−10.46, 0.84)	0.09
Hospital-acquired CRA infection rate[c]	–	–	1.47 (0.92, 2.01)	< 0.001	−0.13 (−1.08, 0.81)	0.77	−0.16 (−0.66, 0.33)	0.50
Hospital-acquired MRSA infection rate	−0.19 (−2.71, 2.31)	0.87	0.49 (−1.15, 1.14)	0.13	−1.15 (−1.74, −0.56)	< 0.001	0.53 (−1.12, 2.20)	0.52
Hospital-acquired VRE infection rate	−6.80 (−9.59, −4.01)	< 0.001[d]	−1.23 (−3.87, 1.39)	0.35	−0.21 (−1.03, 0.60)	0.60	1.56 (1.05, 2.06)	< 0.001
Urinary tract infection rate	−0.96 (−4.13, 2.20)	0.54	−0.59 (−1.27, 0.08)	0.08	0.09 (−0.94, 1.12)	0.85	−1.25 (−3.21, 0.70)	0.20

Abbreviations: LOS: length of stay; NICU: newborn intensive care unit; ED: emergency department; ADE: adverse drug events; CDiff: Clostridium Difficile; CRA: Carbapenem-resistant Acinetobacter; MRSA: Methicillin-resistant Staphylococcus aureus; VRE: Vancomycin-resistant Enterococci; EHR: electronic health records; CI: confidence interval.

[a] Denotes measures with a similar significant immediate effect in 3 or more regions.

[b] We were not able to collect data for time to complete radiology tests in region 4 due to a different parametrization of radiology data.

[c] Abdominal hysterectomy infections in region 5 and CRA infections in region 1 did not have enough cases to fit the statistical model.

[d] Denotes a significant difference between the two groups caused by a significant difference that happened in the control sites.

Table 7
Over time effect for hospital measures.

Measure	Region 1 vs. Control Coefficient (95% CI)	p Value	Region 2 vs. Control Coefficient (95% CI)	p Value	Region 4 vs. Control Coefficient (95% CI)	p Value	Region 5 vs. Control Coefficient (95% CI)	p Value
Quality of care measures								
Hospital LOS	−0.01 (−0.01, 0.01)	0.54	−0.01 (−0.01, 0.01)	0.54	0.02 (−0.01, 0.05)	0.19	−0.01 (−0.02, −0.01)	< 0.001
Mortality rate	0.01 (−0.01, 0.02)	0.13	−0.01 (−0.02, 0.02)	0.84	0.01 (−0.01, 0.03)	0.56	−0.05 (−0.09, −0.01)	0.01
NICU admissions	−1.00 (−1.36, −0.64)	< 0.001	−0.83 (−1.59, −0.08)	0.03	−1.23 (−2.09, −0.38)	0.005	−0.39 (−1.17, 0.38)	0.31
NICU LOS	0.10 (0.01, 0.19)	0.04	0.20 (0.07, 0.33)	0.002	0.14 (−0.06, 0.36)	0.16	0.37 (−0.04, 0.80)	0.08
Patient satisfaction rate	0.24 (0.08, 0.40)	0.004	−0.05 (−0.22, 0.12)	0.55	0.10 (−0.14, 0.35)	0.40	0.37 (0.07, 0.67)	0.01
Pressure ulcer rate	−0.01 (−0.02, 0.01)	0.70	0.01 (−0.01, 0.01)	0.43	−0.01 (−0.03, 0.01)	0.35	−0.05 (−0.09, −0.02)	0.001
Readmission rate	−0.01 (−0.01, 0.01)	0.87	−0.23 (−0.77, 0.29)	0.37	0.41 (−0.37, 1.21)	0.29	1.28 (−0.62, 3.18)	0.18
Productivity measures								
ED LOS[a]	−0.01 (−0.01, 0.01)	0.61	−0.02 (−0.02, −0.01)	< 0.001	−0.04 (−0.06, −0.03)	< 0.001	−0.08 (−0.10, −0.06)	< 0.001
ED visits	3.97 (−5.32, 13.27)	0.39	−4.63 (−22.70, 13.43)	0.61	−0.17 (−33.32, −1.40)	0.03	−44.27 (−62.89, −25.65)	< 0.001
ED wait time[a]	−0.27 (−0.49, −0.06)	0.01	−0.56 (−0.84, −0.28)	< 0.001	−1.26 (−1.46, −1.05)	< 0.001	−1.33 (−1.72, −0.94)	< 0.001
Employees movement rate	−0.03 (−0.06, −0.01)	0.001	−0.03 (−0.07, 0.01)	0.08	−0.02 (−0.05, 0.01)	0.11	0.15 (0.08, 0.22)	< 0.001
Employee turnover rate[a]	−0.01 (−0.02, 0.01)	0.12	−0.01 (−0.02, −0.01)	0.04	−0.04 (−0.07, −0.01)	0.007	−0.13 (−0.16, −0.09)	< 0.001
Hospitalizations	−5.82 (−8.82, −2.82)	< 0.001[e]	3.35 (−1.27, 7.98)	0.15	1.85 (−11.28, 14.98)	0.78	−4.76 (−16.02, 7.49)	0,40
Electronic orders rate[b]	−0.03 (−0.11, 0.04)	0.40	−0.08 (−0.12, −0.03)	0.001	−0.01 (−0.08, 0.05)	0.66	−0.26 (−0.36, −0.17)	< 0.001
Laboratory test orders	−134.36 (−300.87, 32.15)	0.11	−666.84 (−1134.87, −198.82)	0.006[e]	−2275.74 (−2924.54, −1626.94)	< 0.001[e]	−4255.47 (−4706.84, −3804.11)	< 0.001
Radiology test orders	18.11 (1.05, 35.17)	0.03[e]	67.71 (39.64, 95.79)	< 0.001[e]	28.38 (−14.48, 71.24)	0.19	−96.93 (−149.56, −44.30)	< 0.001
Time documenting in EHR[b]	0.05 (−0.07, 0.17)	0.41	0.04 (−0.03, 0.12)	0.21	−0.48 (−1.16, 0.18)	0.14	−0.72 (−1.16, −0.27)	0.003
Time to complete radiology tests[a,c]	−0.19 (−0.26, −0.12)	< 0.001	−0.20 (−0.29, −0.12)	< 0.001	–	–	−0.37 (−0.47, −0.28)	< 0.001
Time to sign radiology tests	0.02 (−0.01, 0.05)	0.07	0.06 (0.05, 0.08)	< 0.001[e]	0.04 (0.02, 0.06)	< 0.001[e]	0.12 (0.10, 0.15)	< 0.001
Patient safety measures								
Abdominal hysterectomy infection rate[d]	0.42 (0.01, 0.83)	0.04	−0.13 (−0.27, −0.01)	0.04[e]	0.58 (0.84, 1.08)	0.02	–	–
ADEs rate	−0.07 (−0.14, 0.01)	0.05	−0.16 (−0.38, 0.04)	0.12	0.12 (−0.02, 0.26)	0.11	−0.13 (−0.30, 0.04)	0.14
Bloodstream infection rate	0.03 (−0.15, 0.22)	0.70	0.09 (0.05, 0.12)	< 0.001	0.05 (0.02, 0.06)	< 0.001[e]	−0.01 (−0.06, 0.04)	< 0.001
Colon surgery infection rate	0.15 (−0.76, 1.08)	0.73	1.37 (−0.02, 2.75)	0.05	1.06 (0.63, 1.48)	< 0.001	0.62 (−0.51, 1.77)	0.27
Falls rate	0.07 (−0.01, 0.16)	0.07	0.05 (0.01, 0.10)	0.04	−0.01 (−0.10, 0.07)	0.74	−0.13 (−0.23, −0.03)	0.007
Hospital-acquired CDiff infection rate	0.03 (−0.77, 0.85)	0.92	−0.22 (−0.40, −0.04)	0.01	−0.39 (−0.60, −0.18)	< 0.001	0.87 (0.65, 1.69)	0.04
Hospital-acquired CRA infection rate[d]	–	–	−0.02 (−0.07, 0.01)	0.18	−0.04 (−0.10, 0.01)	0.13	0.02 (−0.03, 0.08)	0.45
Hospital-acquired MRSA infection rate	−0.01 (−0.22, 0.21)	0.96	0.08 (0.02, 0.13)	0.005	0.05 (−0.01, 0.12)	0.15	0.07 (−0.29, 0.44)	0.68
Hospital-acquired VRE infection rate	−0.64 (−0.94, −0.35)	< 0.001[e]	0.03 (−0.22, 0.29)	0.79	0.19 (0.12, 0.26)	< 0.001[e]	0.06 (0.02, 0.10)	0.004
Urinary tract infection rate	−0.06 (−0.25, 0.11)	0.47	−0.11 (−0.19, −0.04)	0.003[e]	−0.07 (−0.21, 0.08)	0.34	0.07 (−0.32, 0.46)	0.72

Abbreviations: LOS: length of stay; NICU: newborn intensive care unit; ED: emergency department; ADE: adverse drug events; CDiff: Clostridium Difficile; CRA: Carbapenem-resistant Acinetobacter; MRSA: Methicillin-resistant Staphylococcus aureus; VRE: Vancomycin-resistant Enterococci; EHR: electronic health records; CI: confidence interval.

[a] Denotes measures with a similar significant over time effect in 3 or more regions.

[b] Electronic orders rate and time documenting in EHR were assessed without control sites.

[c] We were not able to collect data for time to complete radiology tests in region 4 due to a different parametrization of radiology data.

[d] Abdominal hysterectomy infections in region 5 and CRA infections in region 1 did not have enough cases to fit the statistical model.

[e] Denotes a significant difference between the two groups caused by a significant difference that happened in the control sites.

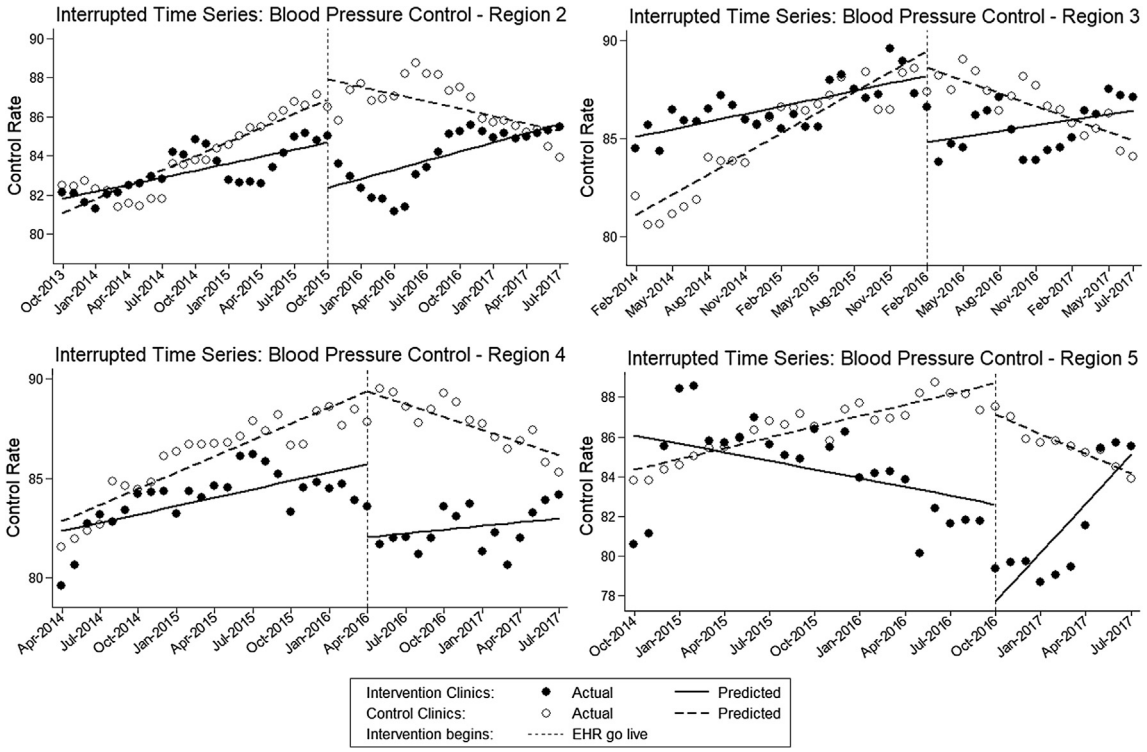

Fig. 2. Example of similar effect across implementation regions: rate of diabetic patients with blood pressure in control in regions 2, 3, 4, and 5.

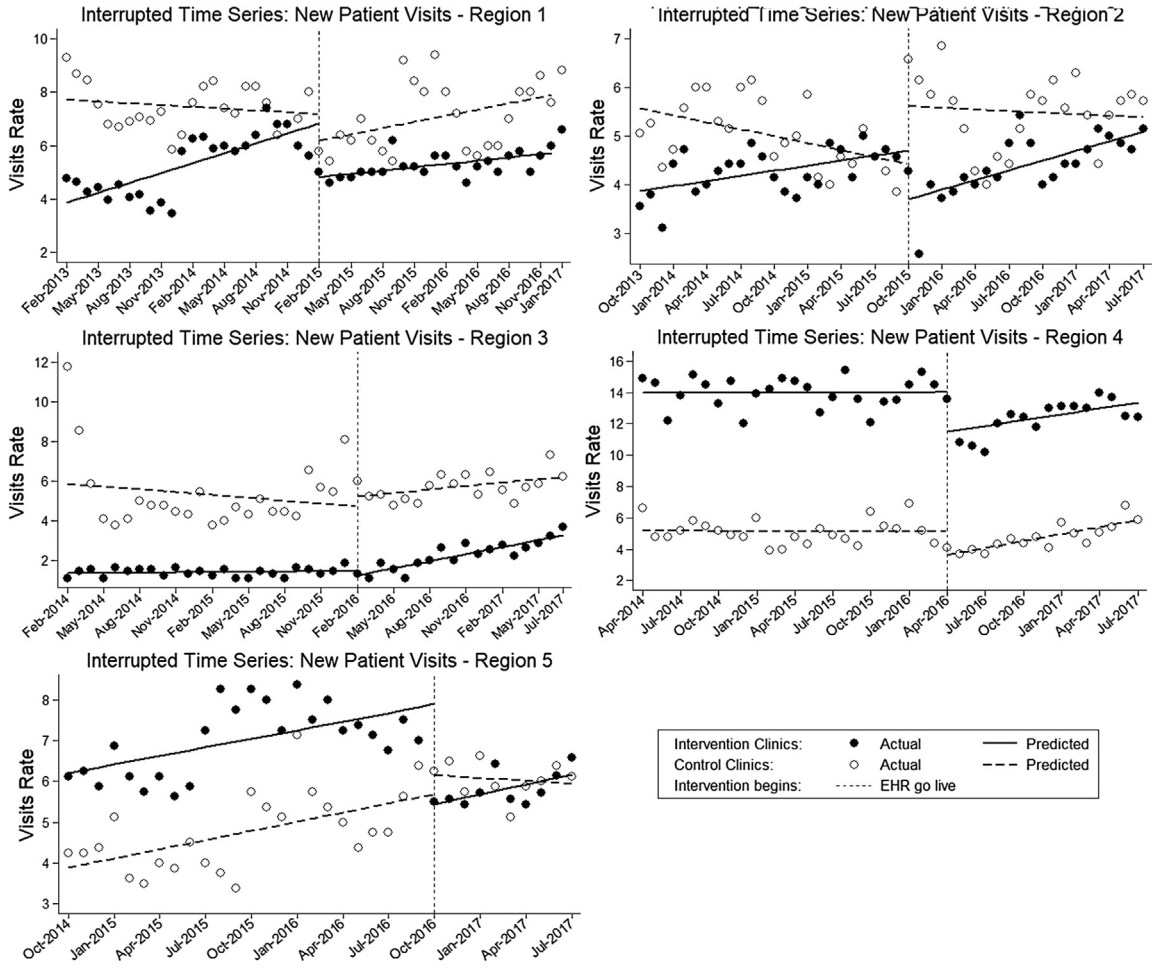

Fig. 3. Example of similar effect across implementation regions: rate of new patient visits in all regions.

detecting the same effect in at least one of the statistical tests in three or more regions (9 measures); *mixed pattern*: measures detecting the same effect in at least one of the statistical tests in two regions with different effects or no significant effects in other regions (9 measures); and *inconsistent pattern:* measures that did not detect the same effect in at least two regions (23 measures). Table 3 summarizes examples of measures for each pattern. Table 4 lists the immediate effect for ambulatory measures, Table 5 lists the over time effect for ambulatory measures, Table 6 lists the immediate effect for hospital measures, and Table 7 lists the over time effect for hospital measures.

4.1. Outcomes with a similar pattern across regions

A similar pattern was detected for four primary care outcomes: "blood pressure control", "laboratory test orders", "new patient visits", and "employee movement rate". A significant decrease immediately after the go live was detected for the first three measures across four regions. Compared to the control group, blood pressure control rate (Fig. 2) decreased significantly immediately after go live ranging from −2.55 ($p < 0.001$) to −3.63 ($p < 0.001$). Such decreases were followed by a significant increase over time in three regions. Blood pressure control recovered to the baseline levels observed immediately before the go live in 7–16 months in two regions and did not recover to the baseline levels in two other regions.

New patient visits rate (Fig. 3) decreased significantly immediately after the go live ranging from −1.01 ($p = 0.001$) to −2.90 ($p < 0.001$). New visits did not consistently recover to the baseline levels observed immediately before the go live during the study period.

Laboratory orders (Fig. 4) decreased significantly immediately after the go live ranging from −157.40 tests ($p = 0.006$) to −796.37 tests ($p = 0.009$). Laboratory orders did not recover to baseline levels observed immediately before the go live in any region.

A similar pattern was detected in five hospital outcomes: "newborn intensive care unit (NICU) admissions", "emergency department (ED) length of stay (LOS)", "ED wait time", "employee turnover rate", and "time to complete radiology tests". The same pattern in ED LOS and ED wait time was detected across four regions.

ED LOS (Fig. 5) increased significantly immediately after go live in four regions, ranging from 0.18 h ($p = 0.02$) to 0.53 h ($p < 0.001$). Such increases were followed by a recovery to the baseline levels observed immediately before the go live in regions 1, 4, and 5, ranging from 10 months in region 5 to 15 months in region 1; region 2 did not recover to the baseline levels during the study period.

ED wait time (Fig. 6) decreased significantly over time in four regions ranging from −0.27 min per month ($p = 0.01$) to −1.33 min per month ($p < 0.001$); however, such decreases represent a recovery from an increase immediately after go live observed in all regions, with a significant difference attributable to the intervention in regions 2, 4, and 5.

4.2. Outcomes with a mixed pattern across regions

Four primary care outcomes detected a mixed pattern: "diabetes bundle", "hemoglobin A1c control", "patient visits", and "radiology test orders". Five hospital outcomes detected a mixed pattern: "patient satisfaction rate", "ED visits", "abdominal hysterectomy infection rate",

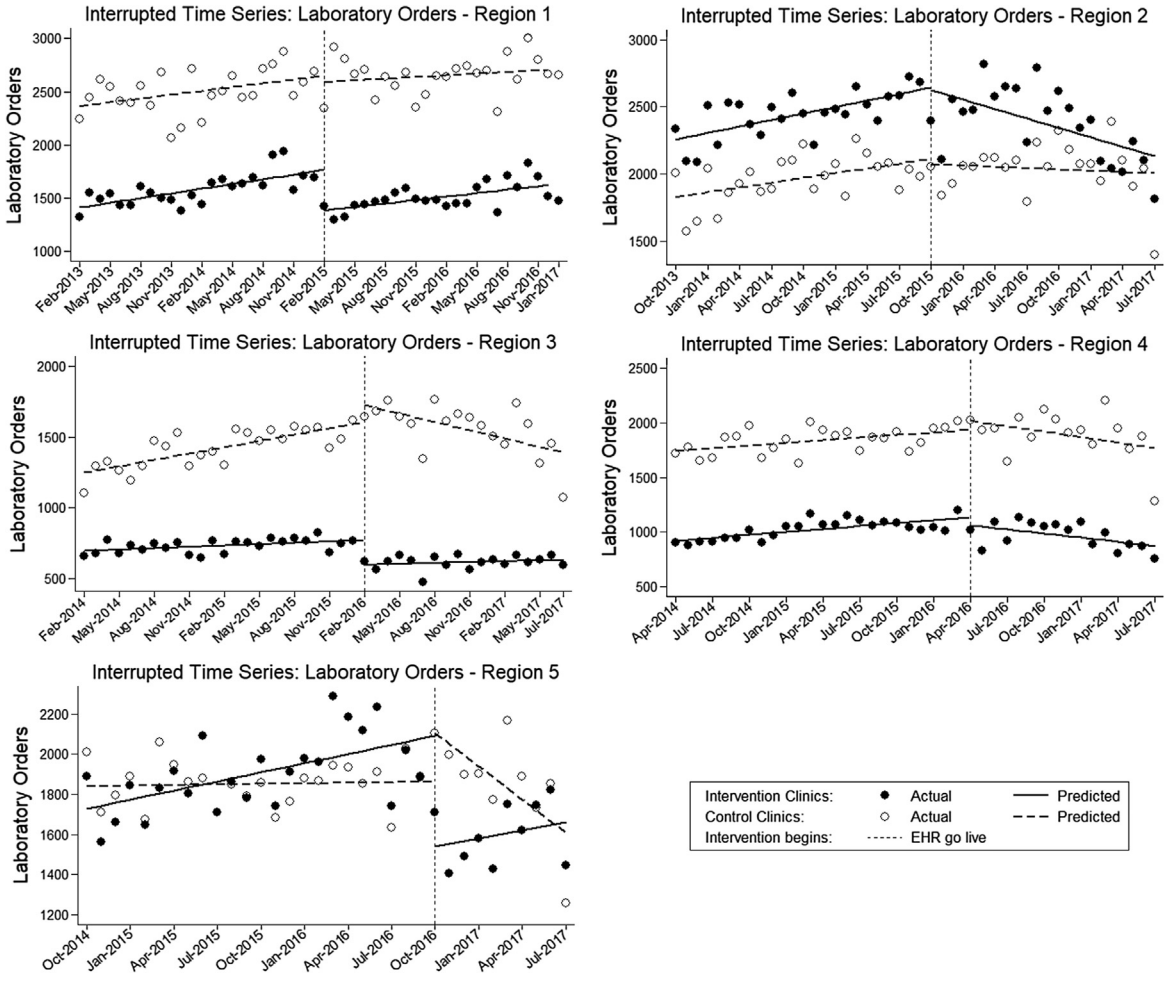

Fig. 4. Example of similar effect across implementation regions: number of outpatient laboratory orders in all regions.

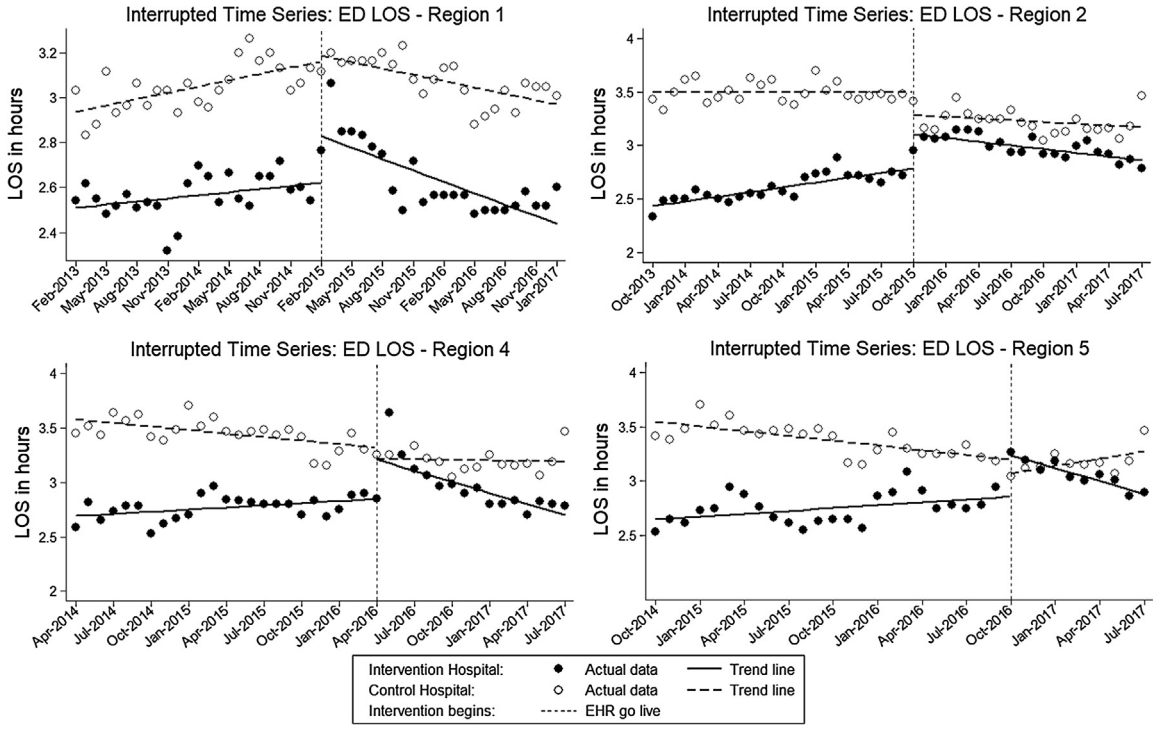

Fig. 5. Example of similar effect across implementation regions: emergency department length of stay in all hospital regions.

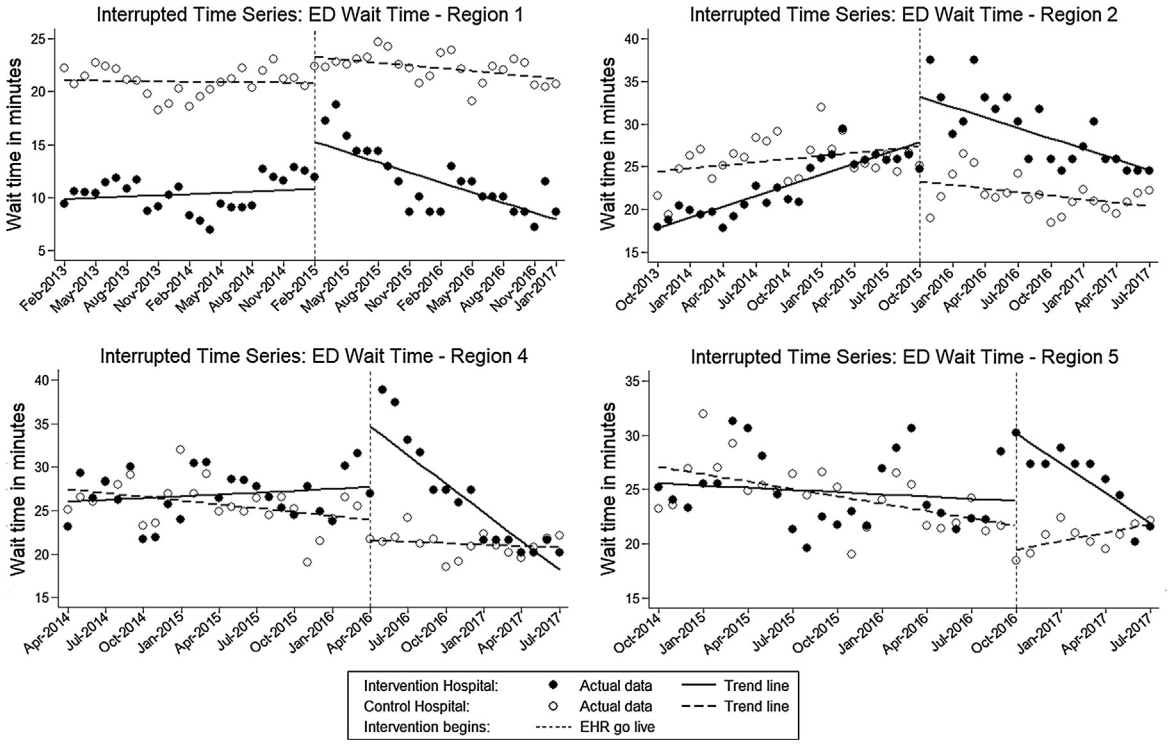

Fig. 6. Example of similar effect across implementation regions: emergency department wait time in all hospital regions.

"colon surgery infection rate", and "hospital-acquired Clostridium Difficile (CDiff) rate".

CDiff infection rate (Fig. 7) for example decreased significantly immediately after the go live in region 1 by −7.11 ($p = 0.05$) and in region 2 by −6.07 ($p < 0.001$). It decreased significantly over time in region 2 by −0.22 per month ($p = 0.01$) and in region 4 by −0.39 per month ($p < 0.001$), whereas in region 5 it increased significantly over time by 0.87 per month ($p = 0.04$).

4.3. Outcomes with an inconsistent pattern across regions

An inconsistent pattern across regions was detected in 23 (56%) of measures.

Four primary care outcomes detected an inconsistent pattern: "medication for asthma", "employee turnover rate", "time documenting in EHR", and "time documenting in EHR after hours". An inconsistent pattern was detected for nineteen hospital outcomes. An inconsistent

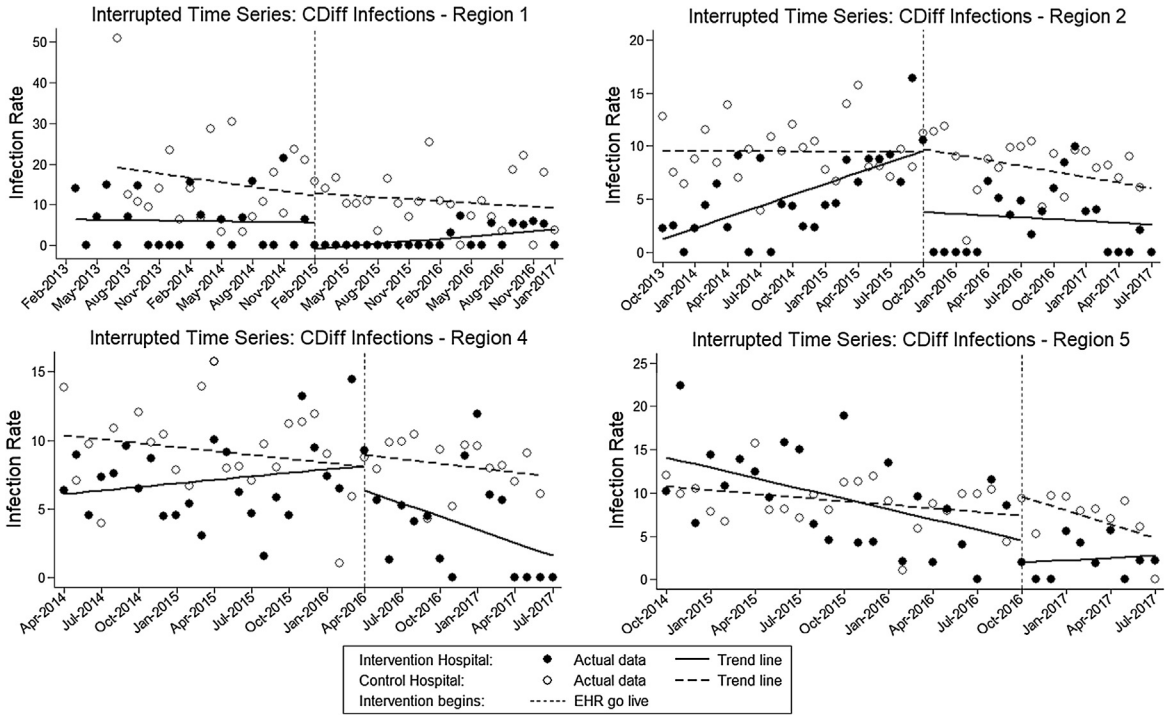

Fig. 7. Example of a mixed effect across implementation regions: hospital-acquired Clostridium Difficile infection rate in all hospital regions.

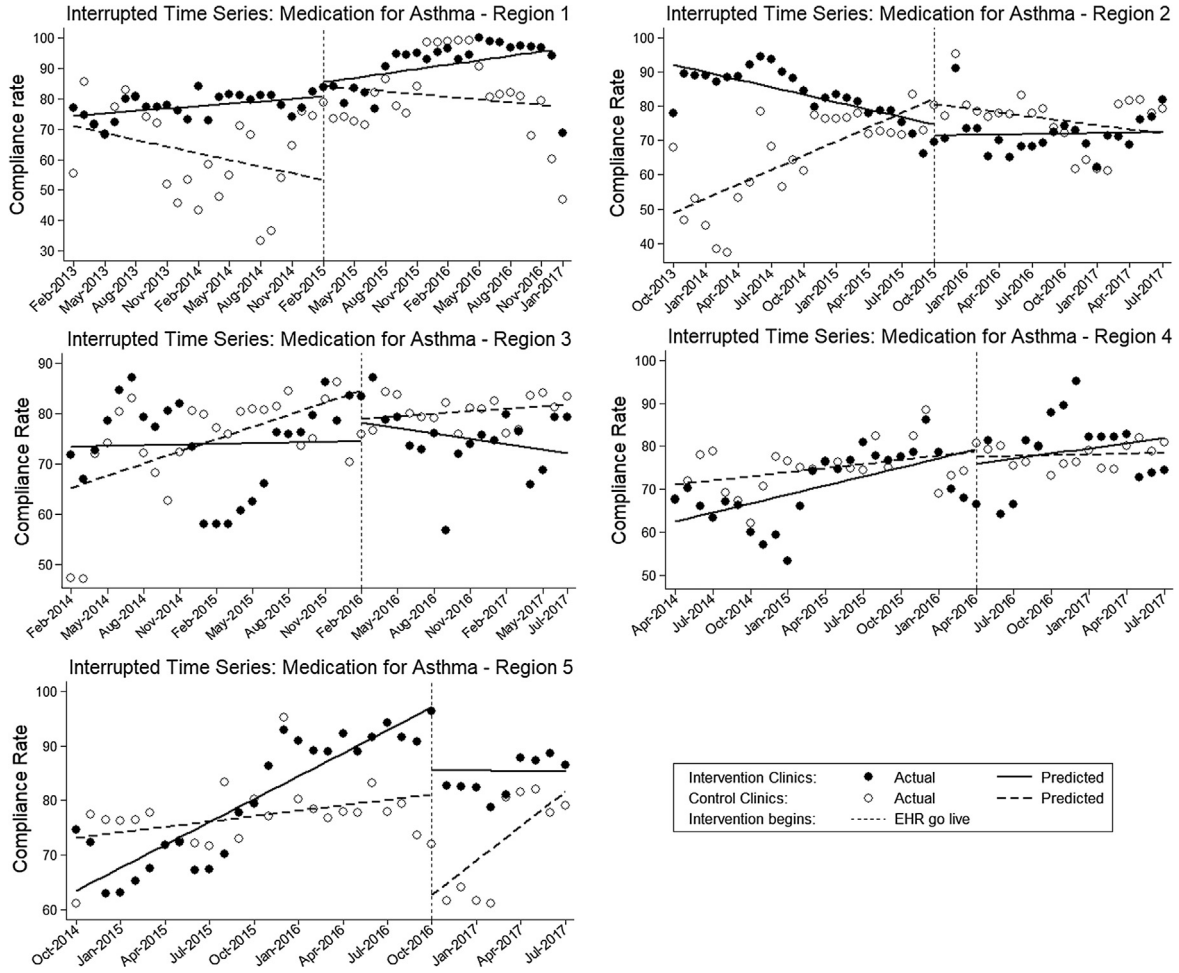

Fig. 8. Example of inconsistent effect across implementation regions: rate of asthma patients receiving controller reliever in all regions.

pattern was detected for five hospital outcomes of quality: “hospital LOS”, “mortality rate”, “NICU LOS”, “pressure ulcer rate”, and “readmission rate”. An inconsistent pattern was detected for seven hospital outcomes of productivity: “employee movement rate”, “hospitalizations”, “electronic orders rate”, “laboratory test orders”, radiology test orders”, “time documenting in EHR”, and “time to sign radiology tests”. An inconsistent pattern was detected for six hospital outcomes of safety: “adverse drug events (ADEs) rate”, “bloodstream infection rate”, “fall rate”, “Carbapenem-resistant Acinetobacter (CRA) infection rate”, “Methicillin-resistant Staphylococcus aureus (MRSA) infection rate”, and “Vancomycin-resistant Enterococci (VRE) infection rate”. “Urinary tract infection” was the only measure for which a significant difference between the two groups was not detected in any region.

An example of a significant difference between the intervention and control group that was detected in only one region was “medication for asthma” (Fig. 8). In this case, intervention sites in region 2 increased significantly over time by 2.57 per month ($p < 0.001$) when compared to control sites.

Although a significant change was detected in “medication for asthma” in region 1, decreasing significantly immediately after go live by −26.04 ($p < 0.001$), such a difference is attributable to a significant increase in control sites. In this region, intervention sites increased immediately after go live by 4.72 ($p = 0.05$), whereas control sites increased by 30.76 ($p < 0.001$). Thus, the significant difference between the two groups was attributable to a change in the control sites.

Individual results for intervention and control groups can be found in Tables 2–19 in the online Supplement, and graphs of outcome measures can be found in Figs. 1–34 in the online Supplement.

5. Discussion

Using our methodology and only data available in electronic format from two distinct EHR systems, we were able to detect various patterns of impact and mixed time-sensitive effects. Such effects would not have been detected by simple pretest-posttest or short-term time-series designs, or by a narrow set of outcome measures. The changes observed in our organization suggest that large commercial EHR implementations in integrated networks introduce performance changes to multiple care processes, but no single measure may consistently detect identical changes in magnitude or pattern. Such changes may affect clinical and non-clinical outcomes after the go live and over time for several months. Organizations implementing EHR systems can implement a similar methodology to detect and fix problems, improve planning for future implementations, and leverage positive effects. Examples of how our method can leverage understanding of health IT impact are discussed below.

A similar pattern across regions was detected for 9 (22%) measures and was more consistently observed in productivity outcomes. ED length of stay and wait time had a similar pattern, consistently increasing immediately after go live with a steady recovery to baseline over time. The prevalence of these effects across implementations and the length of the impact lend support for implementing strategies such as workflow redesign or allocation of “technology champions” for go live support to improve clinician efficiency in time-constrained departments such as the ED. These strategies must be implemented for at least one year after go live, as demonstrated by our findings. Laboratory orders in ambulatory settings decreased immediately after go live in four regions. Total patient visits decreased significantly immediately after go live in regions 4 and 5. Two possible explanations for this pattern are the relationship between the volume of visits and tests ordered, and a decrease in inappropriate orders due to the implementation of system-wide order sets, as reported in previous studies [24,25].

Blood pressure control and NICU admissions were the only quality measures with a similar pattern across regions. NICU admissions decreased significantly over time in three regions. In regions 1 and 2, the decrease over time may have been the result of a recovery from a significant increase after the go live. Another potential explanation is patients were routed to non-implementation regions to reduce workload at implementation sites. Blood pressure control rate decreased after the go live in four regions followed by a recovery to baseline levels in two regions. It is important to note that blood pressure control in diabetic patients tends to decrease in the winter [26]; such a pattern was observed across control regions with declines usually starting between October and November followed by recovery between February and March. In the intervention sites, this pattern was disrupted in regions 2 and 5, which went live in the fall. Such seasonal effects must be considered when choosing the most appropriate go live time.

A mixed pattern across regions was detected for 9 (22%) measures evenly distributed across the categories of quality (3 measures), productivity (3 measures), and safety (3 measures). Examples include diabetes bundle that decreased over time in two regions and increased in one, and CDiff infections, which decreased immediately after the go live and over time in two hospitals, and increased over time in one. Employee turnover increased significantly in two ambulatory and two hospital regions, which may suggest an effect of an increasing EHR-associated physician burnout [6,7].

Overall, an inconsistent pattern across regions was detected for 23 (56%) measures, including two-thirds of hospital outcomes. An inconsistent pattern was also observed for most measures of quality and safety, which seem to have been less affected by the implementation. The variability of effects observed across regions is challenging to interpret. It is likely that some measures could have been influenced by organizational factors affecting outcomes during IT adoptions, as observed in assessments of IT adoptions in other sectors of the economy [27]. The large number of measures with this pattern attests to the need for monitoring a large and diverse set of outcomes during commercial EHR implementations, since contextual differences across implementations may affect different measures. In addition, a large set of measures can facilitate identification of both consistent and isolated negative changes, allowing organizations to react to identify root causes and try to mitigate unexpected effects or plan for the long-term impact of those effects.

A significant difference between the intervention and control groups attributable to changes that happened in the control sites was detected for nearly half of the measures. Most of these differences were detected in only one region. Possible explanations include exposure to organizational factors that could have affected outcomes; seasonal patterns affecting specific populations such as diabetes [26] and asthma patients [28]; and an indirect effect of the implementation in control sites (e.g., resources diverted from non-implementation regions to implementation regions).

Other complex industries such as aviation have mandatory continuous monitoring of safety measures for near real-time detection of adverse effects [29]. In health care, similar reporting is required by policy makers [30] and the government [31], although with an underlying focus on payment and provider benchmarking, and most often done retrospectively. Although the interrupted time-series method has been applied to previous health IT evaluations, previous studies fell short on the use of a comprehensive set of outcomes likely impacted by health IT interventions [32]; and monitored the impact of specific EHR functionality such as computerized provider order entry [33] as opposed to entire EHR implementations. Our study findings indicate that the outcomes affected by large EHR implementations can vary substantially, with some measures demonstrating a similar pattern across implementations, while others show mixed or inconsistent effects. These effects may also be different across institutions, EHR products, and time. Therefore, we recommend an ongoing, near real-time, and systematic monitoring of EHR implementations with a broad set of measures, similar to approaches adopted in the aviation industry. Monitoring should be present not only during the transition phase, but also continuously to detect changes caused by new versions,

implementation of new modules, subtle changes introduced through system configuration (e.g., CDS alerts, order sets), system malfunction, and human adaptation. The measures can be tracked on a monthly basis or even near real-time depending on data availability. For example, if ED LOS data are available weekly, or even daily, monitoring of such an outcome can be done prospectively, and unexpected effects introduced by the new EHR implementation can be readily identified and properly mitigated. Most measures included in our previously published inventory [17] allow such a near real-time monitoring.

With an almost ubiquitous adoption of EHR systems [1,2], with many large integrated networks and academic medical centers adopting commercial EHRs [34–36], it is critical for health care organizations to systematically monitor their EHR implementations. By implementing approaches similar to the one described in our study, organizations will be able to increase detection of significant deviations from baseline performance and implement strategies to mitigate negative effects and leverage positive ones. Furthermore, our method can be used in retrospective analyses of previous implementations to identify what and for how long outcomes were affected, and enable more comprehensive and standardized reporting of evaluations of EHR implementations, hopefully leading us to a better understanding of the full impact of health IT interventions.

5.1. Limitations

Although our methodology effectively detected various outcome changes that correlated with the EHR implementation, these changes do not imply a causal relationship. To mitigate this limitation, we are currently conducting a complementary qualitative analysis to identify both organizational factors introduced by the new EHR implementation that could help explain the effects detected in the present study, and potential covariates to add to our statistical model in future evaluations. The implementation strategy constrained selection of optimal control sites; intervention and control groups had different characteristics, such as different patient volumes. We mitigated this limitation by making comparisons within each group before comparing between groups. Our study did not assess outcome variability in the control sites or a potential indirect effect of the implementation on these sites, nor did it focus on identifying ongoing changes introduced to the new EHR during the study period, such as efforts to optimize user experience and workflow; such changes were likely implemented at the intervention sites and may have contributed to changes in the outcomes. Due to the implementation in control sites, we were able to collect data for these settings only until July 2017, which could have hampered detection of significant effects in some cases. The commercial EHR implemented at Intermountain Healthcare replaced legacy homegrown systems. It is unknown whether this compromises generalizability to settings replacing a commercial EHR with another commercial product; nonetheless, the proposed methodology does not rely on any of the components of the legacy system and could be applied to any setting using any EHR system. Finally, large-scale implementations will inevitably force organizations to operate in a contingency mode (e.g., intentional decrease in the volume of work), and such a contingency may have affected the outcomes measured; however, the proposed method is designed to capture system-wide changes introduced by the implementation itself, and not only by the use of the new EHR system.

6. Conclusions

We successfully implemented a systematic methodology to monitor changes in multiple outcome measures during a health IT intervention. We demonstrated that our method is able to detect various patterns of impact and mixed time-sensitive effects and we argue that it can also be used for continuous monitoring of changes introduced by ongoing maintenance after the system becomes stable following a large implementation. We conducted a robust evaluation of a large-scale commercial EHR implementation including 4 medium-size hospitals and 39 clinics from 5 regions of the same care delivery system. A similar pattern of impact across implementation regions was detected in 9 (22%) measures, a mixed pattern in 9 (22%) measures, and an inconsistent pattern in 23 (56%) measures. Our results and methodology will guide the broader medical and informatics communities by informing *what* and *how* to continuously monitor in similar future implementations. Furthermore, it can be used for early identification of perturbations that can lead to analysis and mitigation of negative impacts.

Conflict of interest

The authors declared that there is no conflict of interest

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jbi.2018.05.018.

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